Topics in Open Economy Macroeconomics: *Currency Choice and Exchange Rate Pass-Through* *and* *An estimated DSGE model of the Hungarian Economy*

Phd Thesis

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Contents

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Introduction

This thesis touches upon three studies in open economy macroeconomics. The first two chapters deal with the endogeneity of exchange rate pass-through. *Chapter 1* deals with empirical observations on the relationship between pass-through and the currency of invoicing and the role of nominal wage rigidities in pass-through determination. A two country endogenous pass-through model is set up to demonstrate the relevance of nominal wage rigidities, openness and the conduct of monetary policy in pass-through determination. *Chapter 2* takes a different perspective on the consequences of the endogeneity of pass-through. Here I focus on the conduct of monetary policy if currency choice is made endogenous. The effects of monetary stability, country size and openness are discussed. *Chapter 3* presents an estimated dynamic stochastic general equilibrium (DSGE) model for Hungary. In this model an adaptive learning mechanism is incorporated into the pricing decisions of firms. In *Chapter 3* I demonstrate how disinflation is captured by inserting a learning rule on *'underlying inflation'* in a DSGE model. Special attention is devoted to what are the consequences of monetary regime changes on the estimated coefficients.

Chapter 1 and *2* deal with the connection between macroeconomic policies, macroeconomic structure and the exchange rate pass-through. First and foremost, let us define what is meant by exchange rate pass-through. Throughout the thesis I call pass-through as the elasticity of prices (either import or consumer prices) to exchange rate changes. However, there is a contradiction between the pass-through term used in the empirical literature and how it is treated in the theoretical models outlined in both Chapters.

While in (traditional) empirical papers pass-through is usually measured by the effect on domestic import prices or consumer prices from an *exogenous* change in the exchange rate. In recent models (and also in those used throughout this thesis) both the exchange rate and prices are endogenous variables. In turn, any connection between exchange rate and prices depends on what type of *exogenous shocks* hit.the economy. This points to one caveat of the traditional empirical literature: pass-through should be shock-dependent and can easily change in time.

One further note should be added: empirical studies usually estimate a different evolution of pass-through to import prices and to consumer prices. However, in the particular models of *Chapter 1* and *2* the two are modelled similarily: i.e. they are linearly dependent. Hence, the theoretical models cannot explain the possible different behavior of the two measure of exchange rate pass-through.

Pass-through is extensively analysed in current open economy macroeconomics. The issue is of high importance in the light of empirical findings that exchange rate pass-through may have declined over the recent years (Gagnon and Ihrig (2004), Sekine (2006)). This has consequences for the conduct of monetary policy and the choice of exchange rate regime, as well.

Generally, the explanations for the decline in pass-through emphasise either the change in *macroeconomic* (most notably monetary) *policies* or the changes in *economic structure*. Taylor (2000) advocated that a stable inflation environment and the endogenous reactions of monetary policies may have created a decline in observed pass-through. This effect has been found to be empirically non-negligible by several studies (e.g. Sekine (2006), Choudri and Hakura (2006), Gagnon and Ihrig (2004) and Gust and Sheets (2006)). Boukez and Rebei (2005) utilised a structural, general equilibrium model for Canada and concluded that pass-through to consumer prices is significantly lower in the inflation targeting period. In their model monetary policy has a key role in the way productivity shocks are transmitted into consumer prices. The shift towards a policy of inflation targeting is largely responsible for the decline in pass-through into consumer prices, but not to import prices.

On the other hand, the *change in product or sectoral structure* may also explain the drop in pass-through. By using disaggregated data Campa and Goldberg (2002) argues that these forces were dominating the *macroeconomic ones*. For example, Corsetti, Dedola and Le Duc (2006) and Dotsey and Duarte (2005) show that growing importance of nontraded services (e.g. distribution sector) may induce a decrease in pass-through.[1]

Besides the vast literature of other theoretical explanations (e.g. menu costs or demand habits etc.), one can also explain the positive relationship between inflation and pass-through with the currency of invoicing i.e. the currency in which prices are held fixed for some periods (Bacchetta and van Wincoop (2003)). Devereux, Engel and Stoorgaard (2004) and most recently Gopinath et al (2007) demonstrate that the currency in which prices are predetermined can be endogenously determined by the optimal behaviour of firms. The fraction of firms choose local currency pricing (LCP) and those opting for producer currency pricing (PCP) determine exchange rate pass-through.

In the model of Devereux et al (2004) relative monetary stability in one country implies a higher fraction of firms setting prices in it's currency. As a consequence, pass-through (measured in domestic currency) falls. The country with relatively more stable monetary policy will gain through monetary stabilisation becoming easier, as lower pass-through enables the central bank to be less responsive to shocks with foreign origins. Foreign shocks have more limited effects on inflation, and thus stabilising inflation becomes an easier task. This is the *'beggar-thy-neighbour'* effect advocated by Devereux et al (2004).

So far, data availability problems served as an obstacle test the models with endogenous choice of currency .Devereux and Yetman (2002) indirectly tested it by fitting pass-through estimates on for example inflation. A recent paper by Gopinath et al (2007) who analyse disaggregated US import price data. They find that there is a large difference in the pass-through of the average good priced in dollars (25 per cent) versus non-dollars (95 per cent). They set up a model with staggered price setting where the choice of currency is endogenous. They claim that their finding is in contrast to the predictions of sticky price

[1] Kónya (2007) has set up a model where pass-through changes are explained by the changing structure of trade: more developed countries produce more goods with price discrimination. Products whose prices are more monopolistically competitive have lower (instantaneous) pass-through, and thus a change in trade structure due to growth (e.g. a reduced role for commodities in production) will reduce pass-through.

models where the currency choice is handled exogenously.

In *Chapter 1* I demonstrate on a cross-country data that the use of domestic currency in invoicing and pass-through estimates (to consumer prices) is negativel related. Pass-through into consumer prices is likely to be lower in countries where importers invoice in their domestic currency. Assuming that the currency of invoicing and the currency in which prices are fixed (at least for some time ahead) this observation serves as the basic motivation to build a model with endogenous currency choice to explain pass-through.

According to my second observation, cross-country regresssion reveals that inflation has a highly significant negative effect on the use of domestic currency as an invoicing currency in imports. Third, I also report that estimated pass-through coefficients to consumer prices and inflation seems to have a positive relationship.

As a fourth stylised fact it is demonstrated that countries with more flexible nominal wages tend to have lower pass-through. The fifth observation is that the relationship between openness (the share of imports in production) and pass-through seems to be quite weak.

Then I build up a model which is motivated by the first fact and argue that numerical simulations of this model can partly explain the remaining four observations. The model is an extended version of the one described by Devereux et al (2004) with productivity and monetary shocks, Calvo-type nominal wage rigidities, endogenous monetary policy reactions and imported intermediates in production.

This model predicts a very different relationship between nominal wage rigidities and pass-through than models with exogenously set currency of invoicing. According to numerical simulations, my robust finding is that countries with flexible nominal wages likely have lower pass-throughs. This conforms to the simple empirical analysis mentioned before.

The model also replicates the empirical evidence that higher monetary stability (lower inflation) is likely to be accompanied by low pass-through. Though it is worth noting that this effect is mostly relevant under productivity shocks and when nominal wages are flexible enough. Monetary policies focusing more on inflation rather than output stabilisation might generate lower pass-through. This might conform to the second and third facts. Note, however, that this result can only be interpreted as conditional on the nature of the shocks.

As regards the connection between openness and estimated exchange rate pass-through. The endogenous pass-through model of *Chapter 1* suggests that by taking into account general equilibrium effects, there might not be a puzzle present.

To sum up, I build a model which predicts that high nominal wage rigidity is likely to correspond to high pass-through and *vica versa*. I present a simple cross-country analysis which seems to support this view. The model also predicts that monetary policies focusing heavily on inlation stabilization can lead to lower pass-through. This effect is mostly relevant if nominal wages are flexible enough. The model also gives an explanation why the relationship between openness and pass-through is found unclear in empirical studies relying on partial equilibrium.

In *Chapter 2* I turn my attention to a different persepctive on the endogenous choice of currency. The question raised here is related to what extent should a central bank (following a strict inflation targeting regime) devote to stabilise imported inflation in an open economy.

Monetary policy in open economies might face a trade-off when pass-through is imperfect. Due to price rigidities, domestic and foreign prices might deviate and output may differ from the socially optimal (frictionless) one. Clarida, Gali and Gertler (2001) and Gali and Monacelli (2005) show that for certain restrictive cases (only price rigidities are present, purchasing power parity holds and imports are used for final consumption), it is enough to stabilise domestic prices to achieve optimal monetary policy. In contrast, Monacelli (2003) demonstrates that if exchange rate pass-through is imperfect, a short-run trade-off between the stabilization of inflation and the output gap arises and hence optimal policy should also smooth out deviations from the law-of-one-price. The presence of wage indexation may also introduce an additional short run trade-off for monetary policy. Campolmi (2006) argues that if wages are partly indexed, policies focusing on purely the price changes of domestically produced goods will be no more optimal.

In the above mentioned studies, however, the extent of price rigidities are assumed to be exogenously fixed. In the endogenous pass-through model of Devereux et al. (2004) an argument is put forward in favour of following *'inward-looking'* monetary policy.[2] In their model monetary policy stabilising domestic money growth rate encourages foreign exporters to prices with Local Currency Pricing (LCP). As a consequence, pass-through into import prices drops. The endogeneity of currency choice creates an *'automatic stabiliser* and the '*inward looking'* policy helps in stabilizing domestic inflation. Note, however, that in these models central banks pursue a strict inflation target: the question posed is how such a central bank can stabilise inflation. In this respect, *'inward looking'* policy is only optimal in this restricted manner.

As mentioned, in the model of Clarida, Gali and Gertler (2001) imports are treated as final consumption goods. According to McCallum and Nelson (2001) if imported goods are in production and pass-through is perfect, controlling inflation in an open economy and controlling inflation in a closed economy requires very similar policies. In contrast, Smets and Wouters (2002) argues that if imports are intermediates and pass-through is imperfect, monetary policy needs to minimize a weighted average of domestic and import price inflation.

As Devereux et al (2004) shows that once pass-through is endogenised in a model without imported intermediates, a strict inflation targeter monetary policy may conduct an *'inward-looking'* policy, I pose the question in *Chapter 2* whether this still holds if imported intermediates are present.

For this, an extended version of the endogenous pass-through model of Devereux et al (2004) is used. Imported intermediates are inserted into this model in the simplest possible way: by a Leontieff-type production function. Interestingly, now country size will also matter in pass-through.

[2] We define *'inward looking policy'* as a policy that stabilises only domestic inflation.

Model simulations reveal that with equal countries and uncorrelated and equally stable monetary policies, inserting imported goods into the production technology does not generate numerically large effects on pass-through. On the other side, in the case of different country size the picture changes. In relatively small countries export price pass-through is likely to be higher. As far as import price pass-through is concerned, the question whether it is higher or not (compared to the equal country size case) depends on the intensity of imported goods used in production.

I find that the original argument of Devereux et al (2004) remains valid if monetary policies are asymmetric. The role of the endogeneity of pass-through is even more emphasised if one introduces imported intermediate goods. In addition, interestingly,.for relatively small countries the *'beggar-thy-neighbour'* effects of endogenous pass-through are even more pronounced. Hence, even in relatively small countries monetary policies can stabilise inflation with the help of endogenous changes in currency choice.

In *Chapter 3* I turn my attention to an estimated two-sector dynamic stochastic general equilibrium small-open-economy model for the Hungarian economy.[3] Two major questions are in focus. As found in the first two chapters and as empirical studies suggest, a change in the conduct of monetary policy to a more price-stability oriented one may have severe consequences for price-setting policies in open economies. The first question is then, how does a change in monetary regime (a switch from an exchange rate targeting regime to a more inflation-focused policy) modify the estimated price and wage Phillips-curves. The second issue raised in this chapter is how disinflation can be modelled in a dynamic stochastic general equilibrium (DSGE) model. I show that introducing a learning process of agents perception on average inflation (the so called *'perceived underlying inflation'*) can help in explaining longer term inflation developments

Hungary serves as a natural example for analysing the above two questions. First, there was a shift in policy in 2001, accompanied by strong disinflation. Second, as Hungary has a history with relatively high inflation rates, agents might have not been fully convinced by low inflation at the outset of the policy switch. I argue that explicitly taking into account the policy switch and a real-time adaptive learning of perceived average inflation may well be of high significance in estimating a DSGE model for Hungary.

The model incorporates different types of frictions, real and nominal rigidities necessary to explain empirical persistence of Hungarian data. The most important departure point from *'standard'* DSGE models is the incorporation of learning in the price formation. Inflation is endogenously decomposed into two parts: a long term (*'underlying'*) and a *cyclical* component. Rule of thumb price setters partly index to their perception on average inflation. The *'perceived'* component of inflation is determined by a real time adaptive learning algorithm. Agents gradually update their perception by the deviation of actual to past perceived inflation. This feature of the model has serious consequences

[3] This chapter is based on my joint paper with Balázs Világi (see Jakab and Világi (2008)).

for inertia in price and wage setting and partly for the reactions of real variables. It is also demonstrated that a Phillips curve for cyclical inflation can be derived. In addition, more *'standard'* frictions are also built in the model. External habit formation in consumption, Calvo-type price and wage rigidity complemented with (i) indexation to past prices and wages, (ii) adjustment costs of investments, (iii) adjustment cost of capital, (iv) labour and import utilisation and (v) fixed cost in production are the major rigidities. Liquidity-constrained rule-of-thumb consumers are also incorporated and imports serve as production input.

The model is then estimated by Bayesian technique, and the posterior density function of the estimated parameters is estimated by the random-walk Metropolis-Hastings (MH) algorithm. As mentioned earlier, the structural break in monetary policy is explicitly taken into account.

The estimated Calvo parameters for consumer prices are close to the eurozone estimates. In contrast, the Calvo coefficients of wages are lower than eurozone levels. Calvo parameters turned out to be relatively stable accross monetary regimes. The regime shift heavily affected the indexation of consumer prices. On the other, wage indexation coefficients are found to be more stable across regimes. In sum, the change in monetary regime in Hungary had some effect on Phillips curves, though mostly the extent of price indexation has changed dramatically. Adjustment cost of investment is found to be high compared to other DSGE models. The estimated value of the interest-rate smoothing parameter is significantly lower than the different euro-area and US estimates.

Impulse-response functions behave qualitatively similarily to other New Keynesian models. The responses of cyclical inflation and cyclical wages are less persistent than those adjusted for agents' perception of average inflation. Due to the high adjustment cost of capital, investments respond to a lesser extent standard in other models. A hump-shaped effect on output and inflation to a monetary tightening is also reported. A positive productivity shock increases output and production, but decreases inflation and employment as documented in Galí (2007). Government consumption shock has a crowding-out effect. Due to rule-of-thumb consumers (non-optimizers) the model generates a co-movement of government and private consumption. The presence of non-optimizing consumers generally has strong implications for short term impulse responses.

Variance decomposition shows that both the cyclical and the *'underlying'* component of inflation can be explained by productivity, investment, consumer preference and markup shocks. Unlike in DSGE models estimated on disinflation periods (e.g. Adolfson et al (2006) for Sweden), the model was capable of explaining longer term disinflation without inserting an additional shock. The DSGE model estimated for Hungary demonstrates that inclusion of learning into a rather standard DSGE model may explain the disinflation process in Hungary. This is shown through an alternative model without endogenous real time adaptive learning of '*underlying inflation*'. Estimation results may point to the conclusion that adaptive learning does not really create an '*intrinsic*' inertia in inflation. Variance decomposition exercice shows that negliging information content of long-term movements of inflation would lead to a model explaining long term inflationary movements only at a very limited extent and the exogenous shock (inflation target shock) is responsible for a large part of inflation movements either in the short or in the long run.

The long run evolution of real variables are explained by the external demand and the productivity shock. This conforms to the intuition that in a small, open economy like Hungary both domestic productivity and export demand drives long term output movements. In contrast to e.g. Smets and Wouters (2003) financial premium and monetary-policy shocks has small explanatory power for real variables. This, however, reinforces the conclusions of Vonnák (2007) and Jakab et al (2006) on the properties of the monetary transmission mechanism in Hungary. The monetary regime shift influenced price setting, but mostly the indexation mechanisms have changed significantly.

The model might be used for policy analysis at the central bank of Hungary (Magyar Nemzeti Bank) in the future. For this purpose, the refinement of the labor market (by e.g. inserting search and marching frictions as in Jakab and Kónya (2008)) or a deeper analysis of optimal monetary policy rules may well serve as a promising avenue for future work.

An earlier version of Chapter 1 was presented at an *internal Workshop* at the Magyar Nemzeti Bank (15th of February, 2007, Budapest), while Chapter 2 was presented at the '*3rd Macroeconomic Policy Research Workshop'* (29-30 October, 2004, Budapest).

The paper which Chapter 3 is based on was presented at the '*The Baltic Central Banks' Research Workshop'* (10-11 May, 2007, Vilnius) at the '*Central Bank Workshop on Macroeconomic Modelling'* (13-14 September, 2007, Oslo), at the *'Annual Conference of the Hungarian Economic Association'* (Magyar Közgazdaságtani Egyesület, 19-20 December, 2007, Budapest), at the '*Meeting of the Working Group on Econometric Modelling of the ESCB'* (February, 2008, Frankfurt) and on the *Course on DSGE Modelling* at the Magyar Nemzeti Bank (during May, 2008). Chapter 3 is forthcoming in the *Working Paper Series of the Magyar Nemzeti Bank*.

Chapter 1

1 Nominal Wage Rigidity and Exchange Rate Pass-Through

1.1 Introduction

Exchange rate pass-through, the extent to which nominal exchange rate fluctuations affect import and domestic prices is a key question in international macroeconomics. A large body of theoretical literature on the conduct of monetary policy (see, for example, Smets and Wouters (2002), Corsetti and Pesenti (2002) and Monacelli (2003)) and on the choice of exchange rate regime (see, for example, Devereux and Engel (2003) and Corsetti and Pesenti (2004)) deals with this question.

In this *Chapter* I seek to understand how estimated exchange rate pass-through coefficients and the choice of currency in foreign trade, inflation and nominal wage rigidities are connected. For this purpose, first I set up some stylised facts by connecting empirical evidence reported in different studies. It comes out that the use of domestic currency in invoicing is negatively related to inflation and estimated pass-through to consumer prices. Some evidence also points to the observation that countries with more flexible nominal wages are more likely to have lower pass-through coefficients. I argue that numerical simulation of a theoretical model incorporating endogenous currency choice and nominal wage rigidities can partly explain the above findings.

There is a wide range of empirical studies reporting that estimated exchange rate pass-through into consumer prices and import prices at the dock (see Gagnon and Ihrig (2004), Gust and Sheets (2006)) has declined in recent years in industrialised countries. Sekine (2006) analysed pass-through to both import prices and domestic prices by using time-varying estimation techniques. He found that both estimated pass-through coefficients have significantly diminished over the past years by an economically non-negligible amount.

Recent literature explained the decline in estimated exchange rate pass-through either by the change in economic structure or by factors related to macroeconomic policies. For example, the former can be captured by the growing importance of distribution or retail services. The appearance of more composite goods accompanied by nontraded services has serious consequences for the variance of nominal exchange rate and may also induce a drop in pass-through coefficients (Corsetti, Dedola and Le Duc (2006), Dotsey and Duarte (2005)).[4]

On the other hand, the emergence of low and stable inflation is also emphasised frequently. The seminal paper of Taylor (2000) argued that the enhanced

[4] Corsetti, Dedola and Le Duc (2005) model real exchange rate volatility with distribution and non-traded sectors, incomplete markets, segmented domestic economies. Their key finding is that in the short run a small amount of nominal rigidities (consistent with the evidence reported by Bils and Klenow (2004)) lowers the elasticity of import prices to exchange rate shocks. They also find long-run exchange rate pass-through coefficients below one.

credibility and the expected reactions of monetary policy has led to low pass-through: as temporary exchange rate variations do not translate into price movements if agents expect a counteracting monetary action in the future.

Boukez and Rebei (2005) shows a structural, general equilibrium model for Canada and estimate a model on two different monetary regimes (pre and post inflation targeting (IT) regimes). They conclude pass-through to consumer prices is significantly lower in the inflation targeting period. Monetary policy has a key role in how productivity shocks are transmitted into consumer prices. The shift towards a policy of inflation targeting is largely responsible for the decline in pass-through into consumer prices.

The role of monetary policy is also emphasised by theoretical models in which pass-through is an endogenous result of firms' pricing policies. In these models the choice of currency depends on optimising behaviour of firms choosing between Local Currency Pricing (LCP) or Producer Currency Pricing (PCP). What is the importance of these models?

Standard open economy models with flexible exchange rates require sticky prices, market segmentation or pricing-to-market behaviour to end up with imperfect pass-through. On the other hand, if nominal exchange rate is volatile, prices in foreign trade cannot be sticky in both (local and producer market) currencies at the same time. Once prices are sticky for certain reasons, the question arises in which currency stickiness is present.

Bacchetta and van Wincoop (2003) first emphasised that the choice of currency of stickiness can also be imagined as an optimal choice of firms. In addition, Devereux, Engel and Stoorgaard (2004) build up a two country general equilibrium model together with endogenous pass-through (currency choice). In their model pass-through hinges upon monetary stability (lower variance of money shocks) and firms are encouraged to fix prices in the currency accompanied by the more stable monetary policy. Consequently, pass-through to import prices (measured in domestic currency) falls if monetary policy is stabilised.[5]

So far, lack of data availability detained the models with endogenous choice of currency to be empirically tested, as data on the use of currency were not collected systematically. The model with endogenous changes in currency choice is tested indirectly by fitting pass-through estimates on for example inflation (Devereux and Yetman (2002)). Another example for testing of the endogenous pass-through model is the recent paper by Gopinath et al (2007) who analyse the invoicing structure of disaggregated US import price data. They find large difference in the pass-through of the average good priced in dollars (25 per cent) versus non-dollars (95 per cent).

In this chapter I attempt to contribute to the literature first by highlighting some empirical facts from a comprehensive and comparable international cross-country database linking data on currency of invoicing and pass-through estimates. Unlike Gopinath et al (2007) I do not onyl collect data for one (the

[5] Corsetti and Pesenti (2004) also endogenises this decision of firms but focused on the optimality of different exchange rate regimes. Interestingly, they arrived at endogenous optimality of both the extreme regimes: either the fixed (currency union) or the free floating exchange rate regime can be optimal if firms can accomodate to it with their pricing strategies.

US), but for several countries. Then, I also show how a model with endogenous pass-through can explain some of the features observed in this data-set.

First and foremost, although limited sample size impeded performing a highly sophisticated econometric analysis, the descriprive analysis shows that there is a significant negative link between estimated pass-throughs (to consumer prices) and the use of domestic currency in invoicing. Pass-through into consumer prices is likely to be lower in countries where importers invoice rather in their domestic currency.

The first stylised fact thus shows that understanding the firms' choice on currency of invoicing may be a necessary ingredient for explaining pass-through. Assuming that invoicing currency works as a good proxy for the currency in which prices are fixed in advance, this may motivate the model of Devereux et al (2004) with endogenous pass-through and also serves as the basic motivation for the theoretical structure of the model used in this *Chapter*.

According to the second stylised fact, cross-country regresssion shows that inflation has a highly significant negative effect on the use of domestic currency as an invoicing currency in imports.

The third observation is that estimated pass-through coefficients to consumer prices and inflation shows a positive relationship. Countries with high inflation rates usually correspond to high pass-throughs to consumer prices.

Fourth, after confronting estimates of nominal wage rigidities and pass-throughs to consumer prices, I find that countries with more flexible nominal wages tend to have lower pass-through. As the sample consists of a few industrialized countries with low and stable inflation, it is unlikely that the observed correlation is a result of the effect that in high inflationary countries wages are relatively flexible and at the same time pass-through is also large. However, the limited sample size does not allow us to identify the sources of this correlation more deeply.

My fifth observation is that the relationship between openness (the share of imports in production) and pass-through is rather weak. Some studies based on partial equilibrium models (e.g. Campa and Goldberg (2006)) suggest that openness, i.e. the growing penetration of imports, makes consumer prices more sensitive to exchange rate shocks. On the other hand, empirical studies (e.g. Choudri and Hakura (2006)) were not able to show a clear dominant or significant role for openness in pass-through. My data-set also suggests a puzzle: higher opennes does not necessarily correspond to higher pass-through.

As shown with the help of numerical simulations of the model (motivated by the first observation) with endogenous choice of currency with special focus on nominal wage stickiness is able to explain the other four stylised facts. The model is an extended version of the one by Devereux et al (2004) with productivity and monetary shocks, Calvo-type nominal wage rigidities, endogenous reactions of monetary policies and imported intermediates in production.

According to simulations a robust finding emerges: the more flexible nominal wages are, the lower the exchange rate pass-through is. This is in accordance with the fourth stylised fact observed in the data.

This is in contrast to the prediction of models with sticky price and wages where price and wage rigidities are handled exogenously. For example, the estimated model of Ambler et al (2003) suggests the opposite: sticky domestic wages slows down domestic pass-through.

The reason is, that in this model firms can optimise either in the usual way (with factor demands and prices) or in a second way. The second channel works through the possibility that firms can determine how their profits are exposed to currency fluctuations. Once, they are allowed to choose their pricing policies an extra degree of freedom arises. This additional channel creates an environment for firms which enable them to more easily accomodate to exchange rate fluctuations, and thus have their profits less exposed to exchange rate movements. The loss arising from being in an environment with sticky wages can be offset by this additional channel. In turn, inserting endogenity of pass-through in a model with sticky wages might compensate for the effects of nominal wage rigidities otherwise having a dampening effect on pass-through.

Numerical simulations also replicate that monetary stability (and correspondingly lower inflation) creates lower pass-through. This might well conform to the second and the third stylised fact reported in this chapter and the seminal argument put forward by Taylor (2000).

One should note, however, that this should only regarded as a a conditional statement. Monetary policies putting a higher weight to inflation rather than to output stabilisation would create an environment of lower pass-through mostly if productivity shocks are the dominant source of uncertainty in the economy and if wages are flexible enough.

As far as the fifth observation is concerned numerical simulation of the model can explain why empirical studies are reluctant to find obvious relationship between openness and pass-through. From the logic of the model, this seems to be not very surprising. In general equilibrium the relationship might take both directions as firms have more freedom to accomodate to certain shocks as they can also change their behaviour with respect to which currency they fix their prices *ex ante*. When wages are flexible enough, higher openness is accompanied by higher pass-through. On the contrary, for a relatively high degree of wage stickiness the relationship is exactly the opposite.

To sum up, first I show that pass-through, the level of inflation and the currency of invoicing are highly correlated internationally. As firms can choose the currency of invoicing freely, understanding this choice may be crucial in explaining differences in exchange rate pass-through. For this purpose, I build a theoretical model with endogenous exchange rate pass-through, nominal wage rigidities, endogenous monetary policy and imported intermediates in production.

Numerical simulations of the model predict that high nominal wage rigidity corresponds to high pass-through and *vica versa*. Moreover, they also predict that an environment with monetary policies focusing *ceteris paribus* more heavily on inflation would lead to lower pass-through. In addition, simulations also suggest that openness and pass-through has non-trivial relationship. In other words, in light of the endogeneity of pass-through the fact that empirical studies are reluctant to find strong effects of openness on pass-through does not seem to be surprising.

This chapter is organised as follows. *Section 1.2* highlights some empirical facts on pass-through, wage rigidities, currency choice and openness. In addition, related theoretical literature and explanations are also summarized here. *Section 1.3* describes the underlying model and its calibration. In *Section 1.4* I turn my attention to the numerical simulation results of the model. Here I focus on the role of nominal wage rigidities, the monetary policy reaction function and openness. In *Section 1.5* conclusions are drawn.

1.2 Empirical motivation

Before turning to an analysis of estimated pass-through one should, however, stress that estimated pass-through coefficients should be only regarded with caution. The empirical literature has serious problems in identifying pass-through elasticities as structural. This is, because these elasticities are often estimated within a partial equilibrium regression. This might be problematic if there are changes in monetary policy regimes, particularily.

In addition, the other problem with partial pass-through estimations is that they rely on data mostly insatisfactory: for example, some proxy foreign prices with foreign CPI, which can be a very poor indicator of the exporters' marginal costs. Pass-through estimates can also be biased as they usually regress stable prices (possibly due to endogenous monetary policy reactions) to noisy nominal exchange rates. Therefore, pass-through estimates may well be biased downwards.

1.2.1 Estimated pass-through and the use of domestic currency in invoicing in imports are negatively related

The first observation is that estimated pass-through coefficients (on consumer prices) and the use of domestic currency in invoicing are negatively related. To demonstrate this, I collected different pass-through estimates and invoicing data for a large set of countries. There is a wide range of pass-through estimates for a number of countries and a database on invoicing currency also exist (see Kamps (2006)). So far, however, these two sources were not put together.

Kamps (2006) publishes a comprehensive data set on the currency of invoicing for both exports and imports for several countries. I borrow empirical pass-through data for different countries from two studies reporting comparable pass-through estimates: data on estimated values of pass-through to consumer prices of Choudri and Hakura (2006) and to manufacturing import prices of Campa and Goldberg (2006).

To estimate pass-through Choudri and Hakura (2006) regress the following equation:

$$\log P_t = \gamma_0 + \gamma_1 t + \Pi_1(L) \log P_{t-1} + \Pi_2(L) \log S_t + \Pi_3(L) \log P_t^* + \varepsilon_t$$

where $\Pi_1(L)$, $\Pi_2(L)$, $\Pi_3(L)$ are lag-polinomials. P_t stands for home CPI, P_t^* represents effective foreign CPI and S_t is nominal effective exchange rates. For each monetary regime they regress a different regression for each country. One should take these results with caution, as foreign variables in this regression might well be only crude proxies. However, by comparing countries, the regression might still be informative.

Campa and Goldberg (2006) estimate sectoral level pass-through by a proxy for marginal costs of exporters (by using GDP and foreign production cost data, as well). The estimated pass-through coefficients are based on the regressions for each countries and sectors:

$$\Delta \log p_{it} = \alpha + \sum_{j=0}^{-4} \alpha_j \Delta \log s_t + \sum_{j=0}^{-4} \beta_j \Delta \log w_{it} + +\gamma \Delta \log y_t + \varepsilon_{it}$$

where $p_{it,}$ w_{it} refers to sectoral prices and sectoral foreign production costs, respectively. s_t and y_t denotes nominal exchange rate and real GDP, respectively. Pass-through regressions of Campa and Goldberg (2006) are less exposed to the mispecified variable-problem as marginal costs of exporters are measured by sectoral level information, as well.

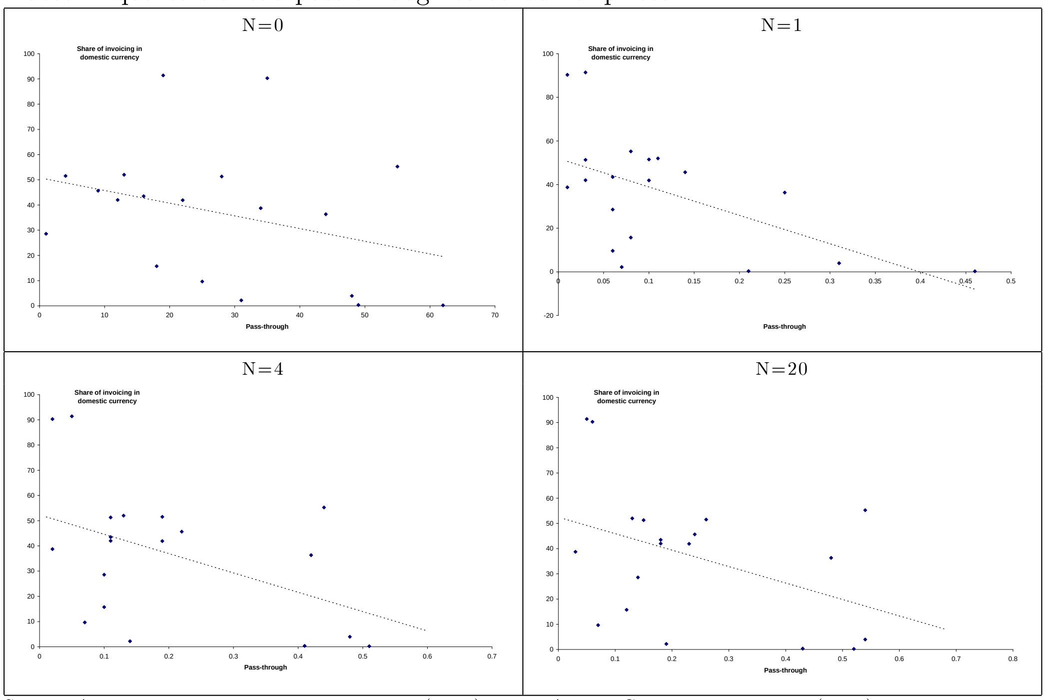
According to *Figure 1.1*, there is a negative relationship between the share of imports invoiced in domestic currency and pass-through to *consumer* prices at any horizons. The more heavily domestic currency is used in invoicing, the lower the pass-through into consumer prices is.

On the other hand, the relationship between pass-through to *import* prices and currency of invoicing is less clear in cross-country dimension. *Figure 1.2* demonstrates that a negative relationship might also be observed (but to a lesser extent) with regards to import price pass-through to manufacturing prices estimated by Campa and Goldberg (2006). However, this relationship seems to be rather weak, as the negative correlation might be due to a few outliers.

Negative relationship between pass-through to import prices and the use of domestic currency is found on US import data in the recent paper by Gopinath et al (2007). They found significantly lower average pass-throughs for goods invoiced in US-dollars than for those priced in other currencies (25 per cent vs. 95 per cent).

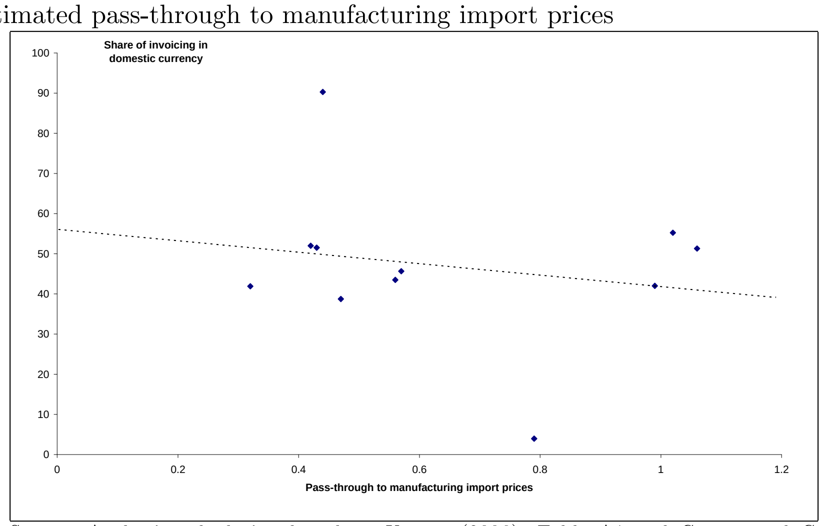
Let us accept that firms fix their prices in the currency of invoicing. Then the observed negative relationship between pass-through and the use of domestic currency in imports also implies a negative association between pass-through and the currency in which prices are fixed. The model outlined later explicitely builds upon this: pass-through is modelled as a result of firms' choice of currency. The crucial assumption in the model exactly lies on this stylised fact.

Figure 1.1 Average share of invoicing in domestic currency in imports and estimated N-quarters ahead pass-through to consumer prices



Source: Author's calculation based on Kamps (2006), Table A1 and Choudri and Hakura (2006), Table 2

Figure 1.2 Average share of invoicing in domestic currency in imports and estimated pass-through to manufacturing import prices

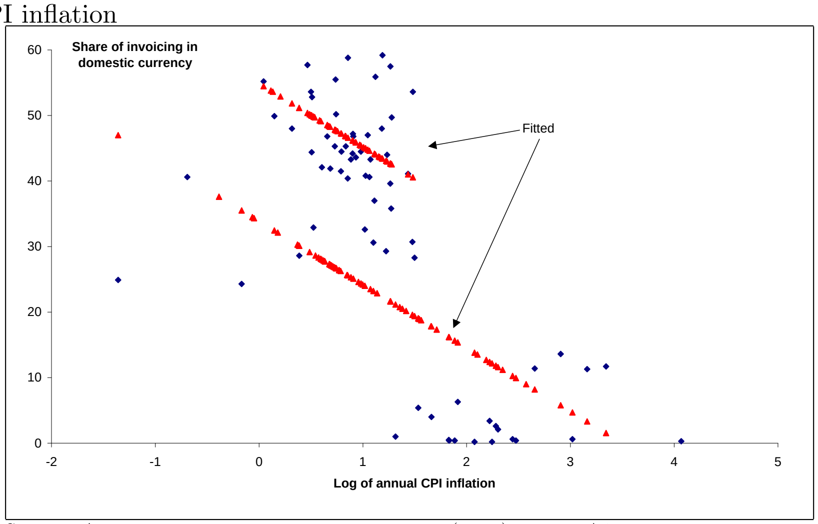


Source: Author's calculation based on Kamps (2006), Table A1 and Campa and Goldberg (2006), Table 1

1.2.2 Negative relationship between invoicing in domestic currency and inflation

I also report that the use of domestic currency as an invoicing currency (in imports) and average consumer price inflation is in a negative relationship.This is demonstrated by *Figure 1.3* and by the cross-country regression. Fims more likely opt for invoicing in the foreign currency if domestic inflation is relatively high.[6]

Figure 1.3 Average share of invoicing in domestic currency in imports and CPI inflation



Source: Author's calculation based on Kamps (2006), Table A1 and International Financial Statistics, fitted values are based on the pooled regression explaining the share of domestic currency invoiced in imports

	Coeff.	Std. error	t-stat	prob
Constant	33.872	3.327	10.180	0.000
log(CPI)	-9.667	1.665	-5.806	0.000
Eurozone dummy	21.027	3.024	6.953	0.000
R-squared	0.681	DW	0.398	
Adj. R-squared	0.671	F-stat	70.332	
Sample	69	Prob(F-stat)	0.000	

1.2.3 Positive relationhip between pass-through and inflation

The seminal paper by Taylor (2000) suggests that stable inflationary environment (low inflation) and the reactions of monetary policy might have created a drop and a slow-down in pass-through.

Sekine (2006) demonstrated this effect empirically: lower pass-through to consumer prices is associated with a low and stable inflationary environment.

[6] Goldberg (2005) also presents an interesting empirical analysis on invoicing with a special focus on new accession countries.

On the other hand, the relationship to the inflation environment was found only weak for pass-through to import prices. The importance of low inflationary environment is also emphasised by Choudri and Hakura (2006) in a new open economy model with Taylor-type overlapping contracts in price setting. They found strong empirical evidence in favour of a positive association between pass-through and the inflation rate. Moreover, they also argued that the average inflation rate was clearly the dominant factor and others, such as import penetration, had only a marginal or insignificant role.

The positive relationship between inflation and pass-through was also reported by Gagnon and Ihrig (2004). Devereux and Yetman (2002) also found positive relationship in a sample of 122 countries. At the same time they also found a non-linearity in this relationship: pass-through increases with inflation, but at a declining rate.

1.2.4 The more flexible nominal wages, the lower pass-through

I argue that the features of the labour market, and in particular nominal wage rigidities, also bear importance in pass-through determination.[7] An empirical connection between pass-through and nominal wage rigidities is shown in *Figure 1.4*. Nominal wage rigidities are measured by the aggregate measure resulting from the International Wage Flexibility Project (*IWFP*), reported by Dickens et al (2006). Some positive connection can be observed between more than one-quarter ahead pass-through estimates (to consumer prices) and the aggregate nominal wage rigidity measure. Countries with more flexible nominal wages are more likely to have low exchange rate pass-through to consumer prices.[8].

One should mention, however, that due to the lack of comprehensive and large data sets on nominal wage rigidity, the empricial evidence can only be treated as indicative. For example, there may well be an endogenity bias: a country with high inflation is likely to be associated with high pass-through (see above) and at the same time nominal wages are likely to be flexible due to high inflation. This data set, however, does not allow us to test for this possibly important bias. On the other, this bias might not be so disturbing, as the countries analysed by the *IWFP* are developed ones and have long lasting low inflationary history. This should, however, be tested for in the future as

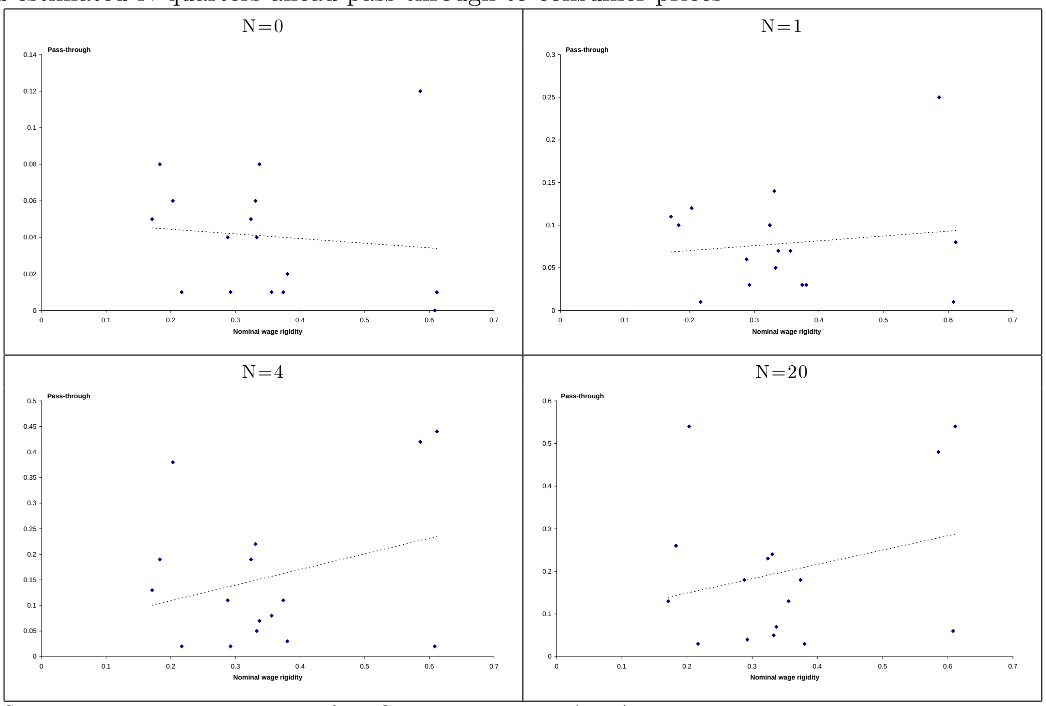
[7] This is in line with the recent wisdom, macroeconomists often emphasise that price-dynamics alone cannot be fully understood without examining how marginal costs react to shocks. Understanding wage formulation (which is a key element in marginal costs) is necessary in order to explain puzzles in pricing (see for example Altissimo et al (2006)). The role of labour market rigidities in price setting (and naturally in pass-through) is thus a natural field for further analysis. A natural question arises: what is the role of wage rigidities in foreign trade price setting.

[8] There is another nominal wage rigidity indicator (based on Holden and Wulfsberg (2007)) which gives a different picture. They measure downward nominal wage rigidity with the *'fraction of nominal wage cuts prevented'*. This measures how reluctant the firms' adjustment is when nominal wages are to be decreased, but due to institutional features of selected economies, it is somehow not allowed. We are, however, not only interested in downward nominal wage rigidities.

empirical literature becomes richer in this respect.[9]

Summing up, I argue that the potential endogeneity bias might not be very strong and therefore, the simple cross-sectional descriptive statistics might support a negative relationship between nominal wage rigidity and pass-through (to consumer prices).

Figure 1.4 Measures of nominal wage rigidity based on the IWF Project and estimated N-quarters ahead pass-through to consumer prices



Source: Pass-through estimates are from Choudri and Hakura (2006), Table 2 and nominal wage rigidity indicators are borrowed from the International Wage Flexibility (IWF) Project (see Dickens et al (2006)) Figure 4,. N refers to quarters[10]

1.2.5 The puzzle of no clear connection between openness and pass-through

There is a puzzle in connection with the role of global trade linkages and pass-through. Empirical analyses on disaggregated (sector level) data have shown

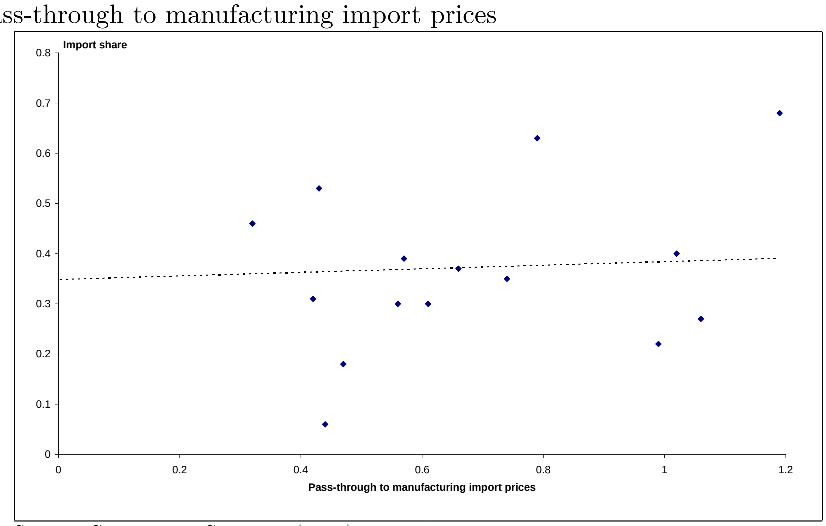
[9] Another option would be to confront macro-level wage-rigidity estimates with pass-through. In this case, the problem arises when comparing the parameters of e.g. estimated DSGE models for different countries. In these models wage-rigidity usually depends on the other parameters of the model (e.g. indexation, price rigidities, elasticities of substitution between different varieties of labor etc.). Hence, the proper way to capture how rigid wages are in these models is to compare impulse response functions for the same shocks. Unfortunately, in my knowledge, there are no studies on comparable impulse responses so far.

[10] I thank the kind help of Jarkko Turunen who provided the data from thK4B835F0.wmft.

changes in trade and industry structure were dominating in the decline in pass-through (see e.g. Campa and Goldberg (2002)). Campa and Goldberg (2006) takes into account three forces determining pass-through to domestic prices: import-price pass-through at the dock, the role of distribution sector and the increasing share of imported intermediates. They advocated that their calibrated sensitivities for OECD countries of domestically produced consumer tradable goods were rising at a faster rate than the price sensitivity of imported goods. This also seems to correspond to intuition, heavier reliance on imported goods would make firms more sensitive to exchange rate fluctuations and thus would raise pass-through. Therefore, one might expect a positive relationship between pass-through and import penetration.

In contrast, empirically, this effect seems to be less important if one looks at aggregate import price pass-through estimates and overall import peneration. According to my limited number of empirical observations, this does not conform to data. Pass-through estimates of Campa and Goldberg (2006) are rarely correlated with the share of intermediates in production (see *Figure 1.5*). This is also reinforced by Choudri and Hakura (2006) where the variable of openness in cross-country regressions was usually inconclusive in the explanation of pass-through. Sekine (2006) found the same puzzle, for most countries the decline in both stages of pass-through (to import and to consumer prices) was related to a rise in import penetration.

Figure 1.5 Share of imported intermediates in production and estimated pass-through to manufacturing import prices



Source: Campa and Goldberg (2006), Table 1 and 3

1.3 A brief overview of theoretical explanations

Taylor (2000) argued that the enhanced credibility and the expected reactions of monetary policy leads to low pass-through: as temporary exchange rate variations do not translate into price movements if agents expect a counteracting monetary action in the future.[11]

Boukez and Rebei (2005) shows a structural, general equilibrium model for Canada, and estimate a model on two different monetary regimes (pre and post inflation targeting (IT) regimes). They conclude that pass-through to consumer prices is significantly lower in the inflation targeting period. Monetary policy has a key role in how productivity shocks are transmitted into consumer prices. The shift towards a policy of inflation targeting is largely responsible for the decline in pass-through into consumer prices. It is worth stressing, however, that pass-through to import prices was not much affected by the shift in monetary regime in Canada.

The importance of low inflationary environment is also emphasised by Choudri and Hakura (2006) in a new open economy model with Taylor-type overlapping contracts in price setting.

Others studies explain the corresponding drop in pass-through and inflation by the growing importance of distribution sector and show that it has serious consequences for exchange rate variability and dampen pass-through, as well (see e.g. Corsetti,Dedola and Le Duc (2006), Dotsey and Duarte (2005)). For example, Corsetti, Dedola and Le Duc (2005) model real exchange rate volatility with distribution and non-traded sectors, incomplete markets, segmented domestic economies. Their key finding is that in the short run a small amount of nominal rigidities (consistent with the evidence reported by Bils and Klenow (2004)) lowers the elasticity of import prices to exchange rate shocks. They also find long-run exchange rate pass-through coefficients below one. These explanations highlight that a relatively high volatility of the nominal exchange rate does not necessarily imply large volatility in consumer prices. Hence, a shift towards floating exchange rates and more focus on inflation stabilization by central banks together with higher nontraded share in production might well explain the drop in pass-through. Moreover, these models are also able to account for the different evolution of pass-through to final consumption goods and import prices.

Standard open economy models with flexible exchange rates require sticky prices, market segmentation or pricing-to-market behaviour to end up with imperfect or low pass-through. However, if nominal exchange rate is volatile, prices in foreign trade cannot be sticky in both (local and producer market) currencies at the same time. Once prices are sticky for certain reasons, the question arises in which currency stickiness is present.

The role of monetary policy is also emphasised by theoretical models in which pass-through is an endogenous result of firms' pricing policies. In these models the choice of currency depends on optimising behaviour of firms choosing between Local Currency Pricing (LCP) or Producer Currency Pricing (PCP).

Assuming that the currency of invoicing may well be a proxy for the currency in which exporters or importers fix their prices, there are several papers

[11] The drop in estimated pass-through can be simply explained by the concatenation of noisy exchange rates together and stability oriented monetary policies can be an explanation for smaller pass-through estimates

postulating a negative relationship to pass-through. In doing so, Bacchetta and van Wincoop (2003) first emphasised the link between pass-through and the currency of invoicing. Devereux, Engel and Stoorgaard (2004) have shown this effect in a general equilibrium model where the currency in which export prices are held fixed (at least for some periods ahead) is endogenous and can be determined by the optimal behaviour of firms. In their model equilibrium pass-through depends on the fraction of firms choosing local currency pricing (LCP) and those opting for producer currency pricing (PCP). Pass-through is then determined by the condition when the *'marginal'* firm is indifferent between the two pricing strategies. Increasing monetary stability (lower variance of money shocks) may motivate more firms to set prices in the currency of more stable monetary policy, and consequently, pass-through to import prices (measured in domestic currency) will fall. This creates a *'beggar-thy-neighbour'* effect *á'lá* Devereux et al (2004). As the relative and not the absolute stabilities of monetary policies matter, the country with *relatively* more stable monetary policy might gain in terms of lowering pass-through, but at more unstable abroad.

Corsetti and Pesenti (2004) also endogenises this decision of firms. Unlike the above authors, they incorporated productivity shocks in the pass-through determination. Their model also reinforced that monetary stability creates low pass-through (although in some set-ups they arrived at corner solutions). In the case of both productivity and monetary shocks, they were able to determine optimal monetary policies by taking into account that pricing policies of firms might also change.

The advantage of '*endogenous*' pass-through model in comparison to other models, is that they can also also explain the link between invoicing and inflation: in these models firms are more likely to fix prices in the currency which has more stable monetary policies (lower inflation). Though, there are disadvantages of these types of explanations. First, as comprehensive data sets were so far missing, the endogenous pass-through model was lacking strong emprical support. The exception is Devereux and Yetman (2002) who calibrated an '*endogenous*' pass-through model and concluded that the model expains that mean inflation tend to increase pass-through, but in a non-linear fashion. They also argue that for sufficiently high inflation rates (or mean exchange rate depreciation rates), price changes occur every period, and exchange rate pass-through is complete.

In *Sections 1.2.1* to *1.2.3*, I add to the literature in the sense that I demonstated empirically that the currency of invoicing generally fits to the conjencture of a simple endogenous pass-through model: importers are are more likely to invoice in the currency with low inflation and invoicing is also related to pass-through.

As far as the role of nominal wage rigidities in pass-through determination is concerned, theoretical literature is less rich. In small open economy models, where price rigidities in the foreign sector (or put differently where pass-through depends exogenously on the structure of the economy) nominal wage rigidities slow down the effects of nominal exchange rate fluctuations to domestic prices.

As an example Ambler et al (2003) estimated a model for Canada and the

United States. Exchange rate pass-through was analysed in a small open economy model with three types of nominal rigidities (nominal wage, domestic and imported price rigidities) and eight different structural shocks. They showed that although pricing to market (the slow adjustment of domestic currency prices of imported goods to exchange rate fluctuations) is necessary to generate slow import price pass-through, it does not necessarily generate slow pass-through to domestic prices. Sticky domestic wages were enough to lead to slow domestic pass-through even when the price of imported goods adjusts immediately to exchange rate fluctuations.[12]

The role of labour market rigidities is clearly highlighted in the endogenous pass-through model of Devereux et al (2004), where it was explicitly assumed that an exogenous fraction of nominal wages (like prices) were set in advance. Devereux et al (2004) also show that their model's predictions are sensitive to the share of wage setters allowed to set wages. One can thus conlude that models with exogenous price rigidities cannot generate the negative correlation between nominal wage rigidity and pass-through as outlined in *Section 1.2.4.*

As far as the ambigous connection of openness on pass-through is concerned (see *Section 1.2.5*) theoretical literature is more or less missing so far.[13]

1.4 The model

I set up a two-country open economy general equilibrium model with endogenous choice of currency in which prices are held fixed in advance. The model explicitely builds upon the first stylised fact that the currency of invoicing (assuming that it corresponds to the currency in which prices are fixed *ex ante*) and pass-through is in a negative relationhip. This motivates the choice of the model based on that of Devereux et al (2004) where this feature is explicitely modelled. The first stylised fact should more or less taken as assumption. As I found that countries with relatively flexible nominal wages are more likely to have low pass-through (to consumer prices) it is also worth building a model where nominal wage rigidities are present. Finally, I conjuncture that a puzzle emerges as contrary to intuition and to partial equilibrium models that openness (import penetration) does not necessarily increase pass-through. In order to seek an answer to this I build a model where imports constitute both final consumption goods and intermediate inputs.

The model is an extended version of Devereux et al (2004) where the choice of pricing policies (LCP or PCP) is made endogenous. Therefore, it is only briefly described and special focus is devoted to the deviation from that.

The first departure point from the model of Devereux et al (2004) lies on the treatment of nominal wage rigidities. In order to have more realistic wage

[12] Maih (2006) also focused on how nominal wage and price stickiness were important in the reaction to shocks with a model with imperfect pass-through.

[13] Other interesting explanation for changes in pass-through is that of Kónya (2007). He sets up a model where pass-through changes are explained by the changing structure of trade: developed countries trade goods with prices more prone to price discrimination. Monopolistically competitive products have lower (instantaneous) pass-through, and thus a change in trade structure due to growth (less role for commodities in production) will lower pass-through.

rigidities, unlike in the original model where part of the wages were exogenously fixed, Calvo-type wage rigidities are inserted. This might give a richer labor market set up.

Second, in order to analyse monetary policies I depart from the simple set-up of Devereux et al (2004) where monetary policy is described by an exogenous setting of money growth rate. For this, a reaction function usually used in the literature is inserted, and therefore monetary policy is endogenised. In my view, this can give a better description of what actual monetary policies are following than simply setting an exogenous monetary aggregate target.

The third deviation is that trade linkages (openness) are also taken into account in production. Imports also enter into the production functions (imports also serve as intermediates). In my view, the role of imported intermediates is worth incorporating in the model, as large part of imports constitute intermediates. Their role, however, is not frequently analysed in open economy models. Indeed, numerical simulations show that the presence of imported intermediates has a *significant* effect on pass-through determination. The reason is that it creates a stronger correlation of firms' marginal costs with nominal exchange rate fluctuations.

1.4.1 Households' problem

There is a continuum number of identical households in both countries, each consumer in the Home country maximises expected lifetime utility, where instantenous utility depends on leisure and current counsumption. Each household owns a firm producing one variety. Each household supplies one unit of labour. There are n households in the Home country and $1-n$ in the Foreign one. Households' problem is to maximize:

$$U_t = E_t \sum_{s=t}^{\infty} \beta^{s-t} u_s \tag{1}$$

where

$$u_s = \frac{C_s^{1-\rho}}{1-\rho} + \frac{L_s^{1+\psi}}{1+\psi} \tag{2}$$

C_s denotes consumption and L_s is labour supply at time s. ρ refers to the elasticity of intertemporal substitution. Consumption basket consists of Home and Foreign produced goods, and the elasticity of substitution between composites is θ. Aggregate consumption is defined as a Constant Elasticity of Substitution (CES) basket of consumption of Home (C_H) and Foreign (C_F) goods.

$$C_t = \left[n^{1/\theta} C_{H,t}{}^{\frac{\theta-1}{\theta}} + (1-n)^{1/\theta} C_{F,t}{}^{\frac{\theta-1}{\theta}} \right]^{\frac{\theta}{\theta-1}}$$

There are six types of consumer goods. Home consumers consume Home produced and two types of Foreign produced varieties. Foreing produced goods are decomposed with respect to how their prices were set. Goods produced by Foreign firms with pricing policies of Local Currency Pricing (LCP) and

Producer Currency Pricing (PCP). Foreign goods are also grouped into three categories: Foreign goods consumed by Foreign consumers, and Home produced goods priced by LCP or PCP pricing policies by Home producers.

There are n Home produced and $1-n$ Foreign produced consumption goods, with elasticity of substitution between individual goods of λ. Hence consumption of Home goods by Home consumers can be described by a basket of $C_{H,t} = \left[n^{-1/\lambda}\int_0^n C_{H,t}(i)^{\frac{\lambda-1}{\lambda}}di\right]^{\frac{\lambda}{\lambda-1}}$ and consumption of Foreign goods by Home consumers as $C_{F,t} = \left[(1-n)^{-1/\lambda}\int_n^1 C_{F,t}(i)^{\frac{\lambda-1}{\lambda}}di\right]^{\frac{\lambda}{\lambda-1}}$.

where i refers to individual varieties of products. Analogously, Foreign consumption (C_t^*) basket is:

$$C_t^* = \left[n^{1/\theta}C_{H,t}^{*\,\frac{\theta-1}{\theta}} + (1-n)^{1/\theta}C_{F,t}^{*\,\frac{\theta-1}{\theta}}\right]^{\frac{\theta}{\theta-1}}$$

with demand for Home produced goods by Foreign consumers as $C_{H,t}^* = \left[n^{-1/\lambda}\int_0^n C_{H,t}^*(i)^{\frac{\lambda-1}{\lambda}}di\right]^{\frac{\lambda}{\lambda-1}}$ and the demand for Foreign produced goods by Foreign consumer as $C_{F,t}^* = \left[(1-n)^{-1/\lambda}\int_n^1 C_{F,t}^*(i)^{\frac{\lambda-1}{\lambda}}di\right]^{\frac{\lambda}{\lambda-1}}$.

Definition of price indices

The (Home) consumer price index (P_t) can be determined as the minimum cost of acquiring 1 unit of aggregate consumption. Hence

$P_t = \left[nP_{H,t}{}^{1-\theta} + (1-n)P_{F,t}^{1-\theta}\right]^{\frac{1}{1-\theta}}$,where $P_{H,t}$ and $P_{F,t}$ denotes the price index of Home and Foreign goods purchased by Home consumers, respectively. Foreign consumer price index (P_t^*) has again an analogous definition $P_t^* = \left[nP_{H,t}^*{}^{1-\theta} + (1-n)(P_{F,t}^*)^{1-\theta}\right]^{\frac{1}{1-\theta}}$.

Now define the price indices of imported consumer goods. As mentioned before, I disentangle two types of imported goods with respect to how their prices were determined. All Home (Foreign) produced goods purchased by Home (Foreign) consumers are naturally priced by Local Currency Pricing policies. A fraction z of Home produced but exported goods are priced with LCP. In addition, z^* refers to the fraction of LCP-priced imported Foreign goods. The shares (z and z^*) will not be exogenous, below I show how they depend on the properties of shocks hiting the economies. For this moment, take these shares as given. Imported Foreing consumer goods are an aggregate of LCP-priced and PCP-priced goods. The price of each LCP-priced goods is $P_{F,LCP,t}(i)$, while the price of PCP-priced Foreign goods in Home currency equals to the

PCP-priced price ($P^*_{F,PCP,t}(i)$) multiplied by the nominal exchange rate (S_t). Hence the price of imported consumer goods in Home currency is an aggregate of PCP and LCP-priced goods, weighted by the shares of differently priced Foreign goods.

$$P_{F,t} = \left[\frac{1}{1-n} \int\limits_{n}^{n+(1-z^*)(1-n)} (S_t P^*_{F,PCP,t}(i))^{1-\lambda} di + \frac{1}{1-n} \int\limits_{n+(1-z^*)(1-n)}^{1} P_{F,LCP,t}(i)^{1-\lambda} di \right]^{\frac{1}{1-\lambda}}$$

The model is symmetric and the price index of Home produced goods consumed by Foreign households (the export price index in the Home country) in foreign currency ($P^*_{H,t}$) is an aggregate of Home produced LCP-priced goods ($P_{H,LCP,t}(i)$) and that of PCP-priced Home goods price in Home currency ($P^*_{H,PCP,t}(i)$) divided by the nominal exchange rate.

$$P^*_{H,t} = \left[\frac{1}{n} \int\limits_{0}^{zn} (P^*_{H,LCP,t}(i))^{1-\lambda} di + \frac{1}{n} \int\limits_{zn}^{n-zn} (P_{H,PCP,t}(i)/S_t)^{1-\lambda} di \right]^{\frac{1}{1-\lambda}}$$

In this model, all prices are set one-period before the shocks hit the economy. Hence there is a direct link between the share of LCP-pricing policies and the short term exchange rate pass-through. As prices are fixed ex ante, only the nominal exchange rate is responsible for short term movements in prices measured in the respective country. The instantenous exchange rate pass-through into the imported consumer price index will be $1-z^*$ in the Home and $1-z$ in the Foreign economy. Exchange rate pass-through into the aggregate Home (Foreign) consumer price index will then be $(1-n)(1-z^*)$ and $n(1-z)$, respectively. If all producers in both countries follow PCP-pricing policies ($z = z^* = 0$), then the short term pass-through to import prices is perfect (unity). Conversely, when all firms have LCP-pricing policies, there will be zero short run pass-through to import prices. As shown later, in the equilibrium all varieties have the same price, hence price indices can be rewritten in a simpler form:

$$P_{F,t} = \left[(1-z^*)(S_t P^*_{F,PCP,t})^{1-\lambda} + z^* P_{F,LCP,t}{}^{1-\lambda} \right]^{\frac{1}{1-\lambda}} \tag{3}$$

$$P^*_{H,t} = \left[z(P^*_{H,PCP,t})^{1-\lambda} + (1-z)(P_{H,LCP,t}/S_t)^{1-\lambda} \right]^{\frac{1}{1-\lambda}} \tag{4}$$

Demands for different types of consumption goods

One can derive the demands for different consumption goods in the standard way. Demand for Home produced goods by Home consumers:

$$C_{H,t} = n \left[\frac{P_{H,t}}{P_t} \right]^{-\theta} C_t \tag{5}$$

Similarly, demand for Foreign produced goods by Foreign consumers:

$$C^*_{F,t} = (1-n)\left[\frac{P^*_{F,t}}{P^*_t}\right]^{-\theta} C^*_t \tag{6}$$

There are four imported consumer goods, an LCP-priced, a PCP-priced Foreign good consumed by Home households, and symmetrically, an LCP-priced, a PCP-priced Home good consumed by Foreign households.

The demand schedules are as follows. Demand for PCP-priced Home goods sold in Foreing country:

$$C^*_{H,PCP,t} = n\left[\frac{S_t P^*_{F,PCP,t}}{P_{F,t}}\right]^{-\lambda}\left[\frac{P_{F,t}}{P_t}\right]^{-\theta} C_t \tag{7}$$

Demand for LCP-priced Home goods sold in Foreing country:

$$C^*_{H,LCP,t} = n\left[\frac{P_{F,LCP,t}}{P_{F,t}}\right]^{-\lambda}\left[\frac{P_{F,t}}{P_t}\right]^{-\theta} C_t \tag{8}$$

Demand for PCP-priced Home goods sold in Foreing country:

$$C^*_{H,PCP,t} = (1-n)\left[\frac{P_{H,PCP,t}}{S_t P^*_{H,t}}\right]^{-\lambda}\left[\frac{P^*_{H,t}}{P^*_t}\right]^{-\theta} C^*_t \tag{9}$$

Demand for LCP-priced Home goods sold in Foreing country:

$$C^*_{H,LCP,t} = (1-n)\left[\frac{P^*_{H,LCP,t}}{P^*_{H,t}}\right]^{-\lambda}\left[\frac{P^*_{ht}}{P^*_t}\right]^{-\theta} C^*_t \tag{10}$$

Budget constraints

Incomplete risk sharing is assumed, consumers can only trade two non-contingent nominal bonds.

Households' budget constraint has the usual form: current consumption and accumulation of nominal bonds (B_t) must be financed by labour income (W_tL_t) and profits (Π_t) plus the revenues earned on assets aquired in the past period ($(1+r_{t-1})B_{t-1}$). r_t denotes the nominal yield of the bond.

$$P_tC_t + B_t = (1+r_{t-1})B_{t-1} + W_tL_t + \Pi_t \tag{11}$$

Profits are total sales minus wage bill minus the costs of intermediate imported goods (see later).

The two countries constitute the world economy, bond holdings (net foreign asset position) of Home households equals to net foreign borrowing of Foreign households ($B^*_t = -B_t/S_t$).

Consumption paths

By taking the first order conditions subject to the budget constraints one can easily derive the Euler-equations describing aggregate consumption dynamics. Note that all decisions are based on date $t-1$ information set. Denoting the Lagrange multiplier for the constraint as Λ_t/P_t marginal utility is:

$$\Lambda_t = C_t^{-\rho} \tag{12}$$

and consumption dynamics is described as:

$$\frac{\Lambda_t}{P_t} = \beta(1+r_t)E_t(\frac{\Lambda_{t+1}}{P_{t+1}}) \tag{13}$$

Similarily, for the Foreign consumer (with Lagrange multiplier as Λ_t^*/P_t^*):

$$\Lambda_t^* = C_t^{*-\rho} \tag{14}$$

and

$$\frac{\Lambda_t^*}{P_t^*} = \beta(1+r_t^*)E_t(\frac{\Lambda_{t+1}^*}{P_{t+1}^*}) \tag{15}$$

It is worth mentioning, that the linear approximations of these conditions (where small-case letters refer to deviation from the non-stochastic steady state) have the following forms:

For Home consumers:

$$c_t = E_t c_{t+1} - \frac{1}{\rho}(r - [E_t p_{t+1} - p_t]) \tag{16}$$

For Foreign consumers:

$$c_t^* = E_t c_{t+1}^* - \frac{1}{\rho}(r^* - \left[E_t p_{t+1}^* - p_t^*\right]) \tag{17}$$

Wage setting

So far the model did not deviate from that of Devereux et al (2004). In contrast to their model, where an exogenously set fraction of wages were set in advance, I allow wages to fluctuate more freely with a Calvo-type wage Phillips-curve.[14] I follow Erceg, Henderson and Levin (1999) and assume that households act as wage-setters. Each type of household j supplies its type of labour to firms, where total labour supply (L_t^S) is a CES-aggregate of individual labour supply in the Home economy (with a wage mark-up term μ^w):

$$L_t^S = \left[\left(\frac{1}{n}\right)^{\frac{\mu^w}{1+\mu^w}} \int_0^n L_t(j)^{\frac{1}{1+\mu^w}} dj\right]^{1+\mu^w} \tag{18}$$

[14] It can be easily shown that using Calvo-type Phillips curve is not very restrictive in the sense that a Rotemberg-type menu cost model may also end up with a similar Phillips-curve. The choice of Calvo-type wage setting lies on its analytical simplicity.

Labour supply in the Foreign country ($(L_t^S)^*$) is:

$$(L_t^S)^* = \left[\left(\frac{1}{1-n} \right)^{\frac{\mu^w}{1+\mu^w}} \int_n^1 L_t^*(j)^{\frac{1}{1+\mu^w}} dj \right]^{1+\mu^w} \tag{19}$$

Each household is a monopolistically competitive wage setter in the market for its type of labour. This implies that he/she sets its labour supply by taking into account the labour demand of firms for his/her type of labour is:

$$L_t^D(j) = \left[\frac{W_t(j)}{W_t} \right]^{-(1+1/\mu^w)} L_t^D \tag{20}$$

Analogously, in the Foreign country:

$$(L_t^D(j))^* = \left[\frac{W_t^*(j)}{W_t^*} \right]^{-(1+1/\mu^w)} (L_t^D)^* \tag{21}$$

Home and Foreign wage indices are then:

$$W_t = \left[\frac{1}{n} \int_0^n W_t(j)^{-1/\mu^w} dj \right]^{-\mu^w} \tag{22}$$

$$W_t^* = \left[\frac{1}{1-n} \int_n^1 W_t^*(j)^{-1/\mu^w} dj \right]^{-\mu^w} \tag{23}$$

Labour suppliers, however face nominal wage rigidities. According to the Calvo setup, workers are only allowed to re-optimize their wages with probability $1-\gamma_w$ each period. Workers take into account that they cannot optimally readjust wages for some time, and from the utility maximization one can arrive at the problem (again expectations are based on date $t-1$ information sets):

$$\max E_t \sum_{s=t}^{\infty} (\beta\gamma_w)^{s-t} \left[\frac{\Lambda_s}{P_s} W_t(j) L_s(j) - \frac{L_s^{1+\psi}(j)}{1+\psi} \right] \tag{24}$$

subject to the constraint given by labour demand. The first-order condition for this problem is then:

$$E_t \sum_{s=t}^{\infty} (\beta\gamma_w)^{s-t} L_s(j) \left[\frac{\Lambda_s}{P_s} W_t(j) - (1+\mu^w) L_s(j)^{\psi} \right] = 0 \tag{25}$$

The same applies for the Foreign workers first-order condtion:

$$E_t \sum_{s=t}^{\infty} (\beta\gamma_w)^{s-t} L_s^*(j) \left[\frac{\Lambda_l^*}{P_s^*} W_t^*(j) - (1+\mu^w) L_s^*(j)^{\psi} \right] = 0 \tag{26}$$

Actual wages are then a weighted average of newly set ($\widetilde{W}_t(j)$) and old wages ($W_{t-1}(j)$) in the Home country evolve according to:

$$W_t^{-1/\mu^w} = \gamma_w \left[W_{t-1}(j) \right]^{-1/\mu^w} + (1-\gamma_w) \widetilde{W}_t(j)^{-1/\mu^w} \tag{27}$$

Wage index abroad is:

$$(W_t^*)^{-1/\mu^w} = \gamma_w \left[W_{t-1}^*(j)\right]^{-1/\mu^w} + (1-\gamma_w)\widetilde{W}_t^*(j)^{-1/\mu^w} \tag{28}$$

Below, the log-linearized versions of these equations are needed. These take the form of the well-known wage-Phillips-curves (and ignoring the index j, as in equilibrium all types of labour has the same wage) in the Home country:

$$w_t - w_{t-1} = \beta E_t(w_{t+1} - w_t) + \frac{(1-\gamma_w)(1-\beta\gamma_w)}{\gamma_w(1+\psi\frac{1+\mu^w}{\mu^w})}(\psi l_t + p_t - \lambda_t - w_t) \tag{29}$$

and abroad:

$$w_t^* - w_{t-1}^* = \beta E_t(w_{t+1}^* - w_t^*) + \frac{(1-\gamma_w)(1-\beta\gamma_w)}{\gamma_w(1+\psi\frac{1+\mu^w}{\mu^w})}(\psi l_t^* + p_t^* - \lambda_t^* - w_t^*) \tag{30}$$

The last term is the difference between marginal rate of subsitution between consumption and leisure to real wages. This would be zero if nominal wage rigidities were absent.

1.4.2 Firms' problem

The treatment of firms' decision deviates from that in Devereux et al (2004) in one aspect. Firms also use imports in production. This will enable us to analyse the role of openness on pass-through and price setting. Firms in both countries are price-setters and decide on factor demands, production and on pricing policies. Firms are identical ex ante, and in equilibrium the only heterogeneity is due to their different pricing policies in their export markets. This homogeneity enables us to simplify the model, although it also restricts us to analyse only some of the features of exchange rate pass-through determination. The production technology deviates from the model of Devereux et al (2004), because I intend to analyse the role of imported intermediates (openness) in pass-through.

Production and factor demands

In each country firms produce goods which can be used for two purposes. Home goods are sold to Home consumers, some part of the production is exported. Exported goods are consumed and used as a factor of production (imported intermediates). Moreover, there is also a distinction between exported goods priced by LCP and those by PCP. For simplicity I assume that the price of imported intermediates and those used for consumption are the same ($P_t^I = P_{F,t}$ and $P_t^{I*} = P_{H,t}^*$[15]). Production of each variety ($Y_t(i)$) is determined by a Leontieff production function with respect to labour ($L_t(i)$) and

[15] As, due to the Leontieff-production function import demand is always proportional to production, relative prices do not have direct impact on real variables. This assumption thus, simplifies the algebra, but does not have significant effect on the final results.

imported intermediates[16] ($I(i)$) and α is the share parameter. z_t^p and z_t^{p*} are total factor productivity shocks.

$$Y_t(i) = z_t^p \min\left[\frac{L(i)}{\alpha}, \frac{I(i)}{1-\alpha}\right] \tag{31}$$

The same technology applies for Foreign firms:

$$Y_t^*(i) = z_t^{p*} \min\left[\frac{L^*(i)}{\alpha}, \frac{I^*(i)}{1-\alpha}\right] \tag{32}$$

Productivity shocks are governed by autoregressive processes (in most of the simulation exercises these shocks are persistent, but stationary):

$$z_t^p = \phi^z z_{t-1}^p + \varepsilon_t^p \tag{33}$$

$$z_t^{p*} = \phi^{z*} z_{t-1}^{p*} + \varepsilon_t^{p*} \tag{34}$$

As in the symmetric equilibrium all firms produce the same amount, hereafter I will ignore the index i. Since technology is subject ot constant returns to scale, MC_t is the marginal cost of a firm that does not depend on production. Moreover, since the production function is Leontieff, marginal cost can be written as a weighted average of nominal wages and imported intermediate costs:

$$MC_t = \frac{1}{z_t^p}\left[\alpha W_t + (1-\alpha)P_t^i\right] \tag{35}$$

Foreign firms marginal costs are:

$$MC_t^* = \frac{1}{z_t^{p*}}\left[\alpha W_t^* + (1-\alpha)P_t^{i*}\right] \tag{36}$$

One can easily derive factor demands in the usual way. Due to the Leontieff-type production function factor demands are linear functions of production. Demand for labour in Home country:

$$L_t^D = \frac{\alpha Y_t}{z_t^p} \tag{37}$$

The same applies for the Foreign demand for labour:

$$L_t^{D*} = \frac{\alpha Y_t^*}{z_t^{p*}} \tag{38}$$

[16] I have chosen Leontieff-type production function due to the following. Imports are suspected to be complements rather than substitutes for labour. By simply introducing a more general production function would create the problem that imports of Home country also constitute demand for Foreign goods, the currency choice and the other part of the model would not be separable. This type of production function was also chosen by e.g. Smets and Wouters (2002) and McCallum and Nelson (2001).

A possible solution would be to incorporate a competetive sector which produces an aggregate good out of the many differentiated goods.

Demand for imported intermediates in Home and abroad:

$$I_t = \frac{(1-\alpha)Y_t}{z_t^p} \tag{39}$$

$$I_t{}^* = \frac{(1-\alpha)Y_t^*}{z_t^{p*}} \tag{40}$$

Firms' price setting

Firms are price setters in both countries. All prices are set ex ante in period $t-1$. Hence firms pick prices as the expected marginal costs times a (constant) markup. In the symmetric equilibrium all firms in the same category (domestic, exporters with LCP and exporters with PCP price policies) charge the same price. Hence, finally there will be only six different prices in the model. The Leontieff-type production function has a clear advantage here. The price setting equations remain similar to that of Devereux et al (2004). Otherwise, the conditions determining currency choice would become rather complicated.

As usual in the literature, the price of Home produced consumer goods in Home currency is (when all prices are equall accross varieties)

$$P_{H,t} = \frac{\lambda}{\lambda-1} E_{t-1} MC_t \tag{41}$$

while the price of Foreign consumer goods in Foreign currency is:

$$P_{F,t}^* = \frac{\lambda}{\lambda-1} E_{t-1} MC_t^* \tag{42}$$

Exporters face a more complex problem. The demand for Home exporters' products can be described as:

$$D(P_t(i)) = (\frac{P_t(i)}{P_{H,t}^*})^{-\lambda}(\frac{P_{H,t}^*}{P_t^*})^{-\theta} C_t^* + (1-\alpha)Y_t^* \tag{43}$$

The first part is the demand for Home consumer goods by Foreign consumers, while the second part comes from the demand for intermediate imported goods of the Foreign economy. (Note that for simplicity I define the individual price ($P_t(i)$) as denominated in foreign currency.)

Optimal pricing policy depends on which strategy is ex ante more profitable. When the firm opts for PCP pricing strategy, its expected discounted profit is:

$$E_{t-1}(\pi_t^{PCP}(i)) = E_{t-1}\left[\beta\left\{P_t^{PCP}(i) - MC_t\right\}\left\{\left[\frac{P_t^{PCP}(i)}{S_t P_{H,t}^*}\right]^{-\lambda}\left[\frac{P_{H,t}^*}{P_t^*}\right]^{-\theta} C_t^* + (1-\alpha)Y_t^*\right\}\right] \tag{44}$$

In the case of LCP pricing policy expected discounted profit is

$$E_{t-1}(\pi_t^{LCP}(i)) = E_{t-1}\left[\beta\left\{S_t P_t^{LCP}(i) - MC_t(i)\right\}\left\{\left[\frac{P_t^{LCP}(i)}{P_{H,t}^*}\right]^{-\lambda}\left[\frac{P_{H,t}^*}{P_t^*}\right]^{-\theta} C_t^* + (1-\alpha)Y_t^*\right\}\right] \tag{45}$$

Now the optimal prices for each price setting policies can be calculated by solving the first order conditions for profit maximization. The problem has the special feature that individual price setting is not affected by foreign demand for imported intermediates, i.e. demand for imported intermediates does not depend on the firm's price, it is proportional to foreign production (due to the Leontieff-type production functions). The separability of consumption and imported intermediate demand is also of a confortable assumption. Optimal LCP price is then:

$$P^*_{H,LCP,t} = \frac{\lambda}{\lambda - 1} \frac{E_{t-1}(MC_t S_t^\lambda A_t)}{E_{t-1}(S_t^\lambda A)} \tag{46}$$

And optimal PCP-price is as follows:

$$P^*_{H,PCP,t} = \frac{\lambda}{\lambda - 1} \frac{E_{t-1}(MC_t A_t)}{E_{t-1}(S_t A_t)} \tag{47}$$

where A_t denotes all factors not affected by individual firms' behaviour ($A_t = \beta(P^*_{H,t})^{\lambda-\theta} C^*_t$).

By using these pricing formulae one can now derive profits under different pricing policies:

$$E_{t-1}(\pi_t^{PCP}) = \Omega \left[E_{t-1}(S_t^\lambda A_t)\right]^\lambda \left[E_{t-1}(S_t^\lambda MC_t A_t)\right]^{1-\lambda} \tag{48}$$

and

$$E_{t-1}(\pi_t^{LCP}) = \Omega \left[E_{t-1}(S_t A_t)\right]^\lambda \left[E_{t-1}(MC)_t A_t)\right]^{1-\lambda} \tag{49}$$

where $\Omega = \frac{1}{\lambda-1}(\frac{\lambda}{\lambda-1})^{-\lambda}$.

After taking a second-order Taylor approximation and comparing expected profits under the two pricing policies one can derive the conditions when the firms choose LCP pricing . The necessary and sufficient condition for choosing LCP pricing is as follows:

$$\frac{var_{t-1}(s_t)}{2} - cov_{t-1}(s_t, mc_t) < 0 \tag{50}$$

where lowercase letters denote logarithms of the oiginal variables. For PCP policy the inequality holds in the other direction.

The condition has two messages. First, pricing policy depends on the expected exchange rate volatility. Second, when deciding on pricing the covariance of (marginal) costs and exchange rates should also be taken into consideration.

Intuitively, when a firm follows LCP strategy, it runs an ex ante exchange rate risk: its sales price is fixed in foreign currency, and thus, revenue fluctuates with nominal exchange rate movements. The more volatile the exchange rate is, the more risky is the revenue in domestic currency, and profits will be more exposed to exchange rate movements. Hence, exchange rate volatility should be negatively correlated with the likelihood of LCP-price setting.

On the other hand, costs can also fluctuate due to exchange rate movements. When costs are highly correlated with exchange rate, then a *'naturally hedged'* position arises: cost fluctuations work in the other direction than that of revenues. The more intensively costs are correlated with the exchange rate, the lesser is profit exposed to it. As a consequence, what matters for choosing LCP-pricing is the relative magnitude of expected variability of the exchange rate and its correlation with (marginal) costs. The opposite holds when opting for PCP-pricing.

For Foreign firms the condition for deciding between different pricing policies can also be stated with a similar derivation. Foreign firms will choose LCP policy if

$$\frac{var_{t-1}(s_t)}{2} + cov_{t-1}(s_t, mc_t^*) < 0 \tag{51}$$

Gopinath et al (2007) derives an analogous formula for optimal currency choice in a model with dynamic price setting by using Bellman-equations. Similarily to the above formulas, currency choice is not conditional on any contemporaneous variables.

Determination of equilibrium exchange rate pass-through

In the above Section the conditions when individual firms choose local currency pricing are derived. The next question is how these conditions can be inserted into a general equilibrium model.

Firms' pricing strategy choices can be treated as a strategic game. Each firm chooses a pricing strategy *ex ante* of fixing its price for one period in foreign or in home currency. Whether this strategy was optimal or not depends on others' behaviour, as well. There are three types of equilibria: two under pure strategies and one under mixed strategies with probabilities of choosing LCP of z and z^*in the Home and in the Foreign countries,respectively.

Equilibria under pure strategies are as follows. If one solves the model for any possible values of z and z^* and the two inequalities hold, then all firms will choose LCP regardless of what other firms do. On the other hand, when for all pairs of z and z^* the conditions do not hold, then all firms will engage in PCP strategy whatever other firms choose. In these cases the pure strategy equilibria are stable.

If equilibria on pure strategies are not stable (there is an incentive to deviate from them for any firm), there can still be equilibrium under mixed strategies.[17] The mixed strategy constitutes a strategy as domestic firms choose LCP price with probability z and Foreign firms with probability z^*. Equilibria under mixed strategies are exactly those when the two conditions on choosing LCP hold as equalities, i.e. firms are indifferent of choosing different pricing rules, in expected terms.

The procedure used to find the equilibrium under mixed strategies is a grid search algorithm. For any possible pairs of z and z^* I solve the model and find

[17] As Devereux et al (2004) solves the model analitycally, they are able to determine the exact conditions for parameter values when equilibria under pure strategies are unstable.

those values where conditions for LCP-pricing hold exactly with equality. [18] One should note, that not all equilibria under mixed strategies are stable, and the stability of any numerical solution should always be checked for.[19]

In sum, equilibrium pass-through is determined by a grid search algorithm: I solve the model for any possible pairs of z and z^*. Finally, equilibrium pass-through is the one which corresponds to those (z, z^*) pairs for which both two conditions for choosing LCP hold as equalities. As a final step, the stability of this solution is also checked. If firms have incentive to deviate from the strategy the solution will be that all firms follow either LCP or PCP.

1.4.3 Market clearing and the current account

Market clearing conditions are the usual ones: domestic consumption equals to sales of Home goods sold at Home plus Foreign consumer goods imported by Foreign LCP-exporters and that of Foreign PCP-exporters. Production of domestic firms is a the sum of domestically sold consumer goods, exported consumption goods and exported intermediate goods.

$$Y_t = C_{H,t} + I_t^* + (1-z)C^*_{H,PCP,t} + zC^*_{H,LCP,t} \tag{52}$$

$$Y_t^* = C^*_{F,t} + I_t + (1-z^*)C_{F,PCP,t} + z^*C_{F,LCP,t} \tag{53}$$

The current account must clear in equilibrium, which means that the current account (trade balance plus foreign interest income) equals the change in the country's net foreign asset position:

$$\begin{aligned} P_tC_t + B_{t+1} &= (1+r_{t-1})B_t + P_{H,t}C_{H,t} + zP_{H,LCP,t}C^*_{H,LCP,t} + \quad (54) \\ &\quad +(1-z)P_{H,PCP,t}C^*_{H,PCP,t} + S_tP^*_{H,t}I^*_t - P_{F,t}I_t \quad (55) \end{aligned}$$

Domestic firms are owned by domestic consumers and thus profits are:

$$\begin{aligned} \Pi_t &= P_{H,t}C_{H,t} + zP_{H,LCP,t}C^*_{H,LCP,t} + (1-z)P_{H,PCP,t}C^*_{H,PCP,t} + \quad (56) \\ &\quad +S_tP^*_{H,t}I^*_t - P_{F,t}I_t - W_tL_t \quad (57) \end{aligned}$$

[18] Devereux et al (2004) analytically solves their simpler model. In this Chapter I only experiment with numerical solution of a more complicated model.

[19] The question arises how firms can coordinate by playing the mixed equilibrium, when they are indifferent between the two policies? The interpretation of Bacchetta and van Wincoop (2003) is exactly the one mentioned above: firms play the mixed strategy with choosing to follow LCP with probability z, before choosing prices (ex ante).

Devereux et al (2004) give an alternative interpretation how coordination is enforced. Assume that there are small firm-specific costs (e.g. menu costs) of choosing LCP as opposed to PCP. If we rank firms increasingly in order of these costs, then the mixed equilibrium would be a limit outcome as the scale of these differential costs approaches zero.

1.4.4 Monetary policy and exchange rate determination

Monetary policy is modelled differently than in Devereux et al (2004). Here, policy is no more exogenous (by setting an exogenous path of money stock with some noise), but a reaction function is inserted. Government in this model only sets nominal interest rates. Monetary policies follow an ad hoc policy rule; a Taylor-type rule with forward looking inflation stabilization and with some weight on actual GDP. In addition, monetary policy also smooths interest rates. However, unlike other agents in the economy, monetary policy might react to inflation outlook based on current information (after realizing exchange rates,wages and prices). Monetary policy knows current shocks, as well. The policy rule is the usual one:

$$r_t = \Xi_i r_{t-1} + (1 - \Xi_i) \left[\overline{\pi}_t + \Xi_\pi E_t(p_{t+1} - p_t) + \Xi_y gdp_t\right] + z_t^m \tag{58}$$

$$r_t^* = \Xi_i r_{t-1}^* + (1 - \Xi_i) \left[\overline{\pi}_t^* + \Xi_\pi E_t(p_{t+1}^* - p_t^*) + \Xi_y gdp_t^*\right] + z_t^{m*} \tag{59}$$

Where gdp_t denotes deviation of actual GDP to its steady state value[20]. For simplicity, I assume that inflation targets ($\overline{\pi}_t$ and $\overline{\pi}_t^*$) are zero. However, monetary policy does not necessarily follow this rule; z_t^m and z_t^{m*} are driven by persistent but stationary processes:

$$z_t^m = \phi^m z_{t-1}^m + \varepsilon_t^m \tag{60}$$

$$z_t^{m*} = \phi^{m*} z_{t-1}^{m*} + \varepsilon_t^{m*} \tag{61}$$

Financial markets are modelled in a simple way through a modified uncovered interest rate parity condition. Future exchange rate changes depend on the interest rate differential and a risk premium term based on Schmitt-Grohe and Uribe (2003). Nominal exchange is thus driven by:

$$\frac{(1 + r_t)\, S_t}{E_t \mathcal{S}_{t+1}} = 1 + r_t^* + \vartheta(e^{-(B_t/\bar{B}-1)} - 1) \tag{62}$$

For future reference I report the log-linearized form of the modified UIP-equation:

$$E_t s_{t+1} = s_t + r_t - r_t^* + \vartheta \hat{B}_t \tag{63}$$

1.5 Calibration and solution

The model parameters are calibrated with values mostly taken from literature. The intertemporal elasticity of substitution (ρ) is set to be 2. Individual goods were treated as close substitutes with λ equal to 5 (implying price markup of 25 percent). Home and Foreign goods were assumed to be not as close substites, with elasticity of substitution (θ) of 2. The inverse of the labour supply elasticity

[20] This is not the output gap measuring a deviation of actual to the stochastic flexible price output. GDP is defined as total sales minus the cost of imported intermediates.

(ψ) has the value of 2 usual in the literature. Time-preference (β) has the value of (quarterly) 0.984.

As a baseline setting, the parameters of the monetary policy reaction function was imported from Lubick and Schorfheide (2004) with an interest rate smoothing parameter (lagged interest rate) of 0.84, the parameter of inflation deviation from target (Ξ_π) of 2.19 and 0.3 for the deviation of output (Ξ_y). In the first alternative policy rule specification I used the original Taylor-rule coefficients of 1.5 and 0.5 for inflation and output, respectively. The other alternative policy rule received a more *'hawkish'* parameter for inflation of 3 (with the other two coefficients remaining the same as in the baseline).

As I analyse the role of different openness (α, import content in the production function) and that of several nominal wage rigidity parameters (probability of fixed wages: γ_w), I ran different scenarios with respect to α and γ_w between 0.1 to 0.9.

Throughout the simulation exercises, countries were of equal size ($n = 0.5$) and all shocks were persistent with autoregressive coefficients ($\phi^z, \phi^{z*}, \phi^m, \phi^{m*}$) of 0.95. The elasticity of nominal exchange rate to debt (ϑ) was given a small value of 0.01.

The model solution proceeds as follows. For each pairs of z and z^*, the model was log-linearized around the nonstochastic steady-state and then solved by the software Dynare (version 3.05) running under Matlab. The values of optimal z and z^* are determined then by a grid search algorithm.

1.6 Results

There are two types of stochastic shocks in the model: monetary rule shocks and aggregate productivity shocks.[21] The basic difference between these shocks lies in their direct effects on the two major determining factors of pass-through; how they alter the variance of the nominal exchange and its covariance with marginal costs.

Monetary rule shocks are such that they modify interest rates in a persistent way. Positive monetary rule shocks mean higher interest rates: a temporary monetary tightening accompanied by an immediate exchange rate appreciation (and through the UIP-condition a subsequent depreciation thereafter).

Monetary shocks have two direct effects in the model: they change the evolution of the nominal exchange rate and also affect consumption paths. The first is through the UIP-condition by altering the nominal exchange rate. The second one is through the change in consumption paths. The latter enters into wage Phillips-curves (by changing the marginal rate of substitution between leisure and consumption). Hence, as an indirect effect, marginal costs are also altered. So there is a direct effect on nominal exchange rate and an indirect effect on marginal costs.

[21] The choice of shocks corresponds to the literature. Devereux et al (2004) and the model in *Chapter 2* analyse monetary shocks, Corsetti and Pesenti (2004) have both productivity and monetary shocks.

The second type of shocks analysed is aggregate productivity shocks. These shocks alter both export and domestic prices and also enter into factor demands. So, there is a direct link between marginal costs and productivity shocks. Their effects on the variance of nominal exchange rate, however, are only indirect: monetary policy reacts to lower prices (inflation) and higher output. Here there are a direct cost effect and an indirect exchange rate effect.

The advantage of this model is that pass-through (or equivalently the pricing policies of firms) is determined by firms' optimisation behaviour. Unlike in standard open economy models, here firms not only choose factor demands and prices, but also determine their pricing policies. In other words, firms are able to optimise with standard channels well-analysed in general equilibrium models. However, they have an extra degree of freedom: they can alter their pass-through coefficients.

This complexity allows us to analyse pass-through in an elegant way, such that it will be shock and economic structure (e.g. the importance of wage rigidities and openness) dependent. Unlike in other models with exogenous pass-through, the model can also say about the relationship of prices, invoicing (as a proxy for which currency prices are predetermined).

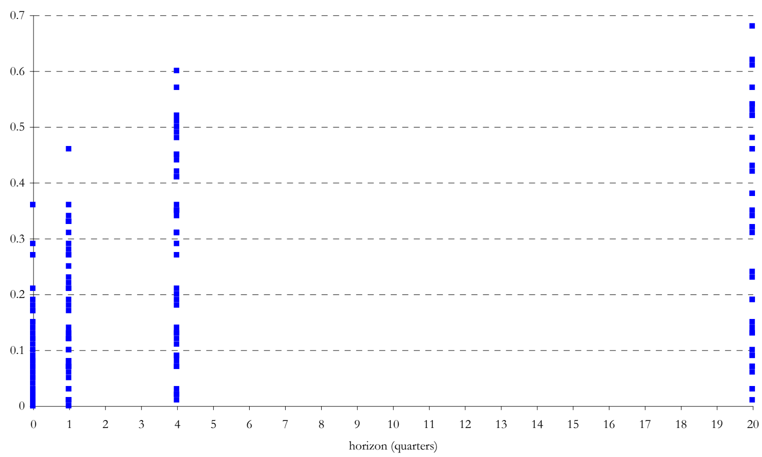
However, there are some disadvantages of this model. First, it does not discriminate between pass-through to consumer prices and to import prices. The two pass-throughs are linear functions of each other. Hence,.the model cannot account for possible different movements in the two pass-throughs, often emphasised by the empirical literature.

Second, as prices are predetermined only for one period, the model cannot capture inflation persistence. It is not very straightforward to shock the model and to calculate covariates between simulated exchange rates and prices, because simulated prices would always deviate from their steady state for only two periods and the resulting correlations would not be really comparable to those observed in the data.

Another caveat of the model is that the presence of asymmetric shocks in this model always leads to corner solutions: all agents price with LCP or with PCP. This is not at odds in the literature. For example, corner solutions were also found by Corsetti and Pesenti (2004) and for some parameters set-ups by Devereux et al (2004). The former model has non-corner solutions with both productivity and monetary shocks and with sufficiently established monetary policy rules. The corner-solution feature of this model comes from the limited role of the heterogeneity of agents. The only source of heterogeneity here is that firms are heterogeneous in the chosen pricing-strategy, but the marginal firm will be indifferent between choosing LCP or PCP pricing. Perhaps a richer heterogeneity between firms (e.g. the distinction between traded and non-traded good producers) might end up with smaller role for corner solutions.

Results for the baseline parametrization can be found on *Table 1.1* and *Figure 1.7*. Simulated pass-throughs point to the important observation: pass-through can vary quite substantially, depending on nominal wage rigidities, openness and the nature of shocks. Simulated values range from around 40 per cent to almost 100 per cent. This might conform with empirical estimates where pass-through ranged between almost zero to 70 per cent (highlighted for example in *Figure 1.6*). This model is flexible enough to generate a wide range of pass-throughs usually estimated in the empirical literature.

Figure 1.6 Estimated exchange rate pass-through to consumer prices*



*Source: Choudri and Hakura (2006), Table 2

Table 1.1 Exchange rate pass-through and share of LCP-price setters under different shocks and parametrisation*

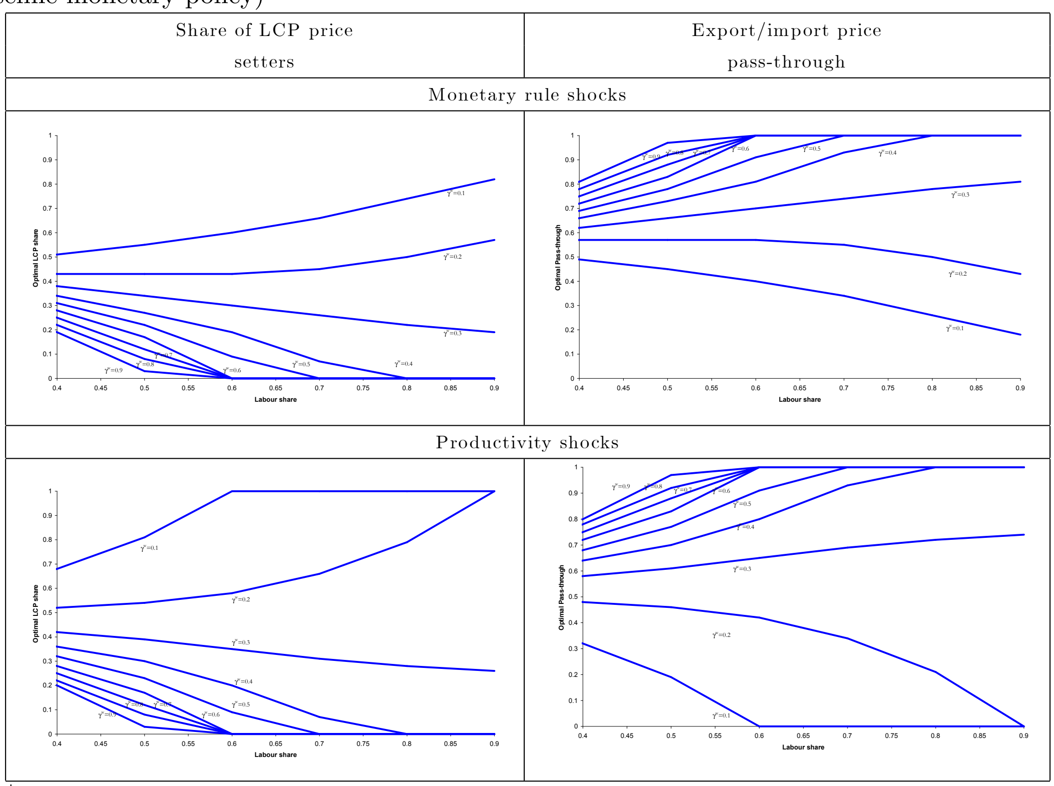
Shocks	Share of LCP-price setters	Import/export price pass-through
$\alpha = 0.6, \gamma_w = 0.2$		
Monetary rule	0.43	0.57
Productivity	0.58	0.42
$\alpha = 0.6, \gamma_w = 0.5$		
Monetary rule	0.09	0.91
Productivity	0.09	0.91
$\alpha = 0.3, \gamma_w = 0.2$		
Monetary rule	0.45	0.55
Productivity	0.50	0.50
$\alpha = 0.3, \gamma_w = 0.5$		
Monetary rule	0.37	0.63
Productivity	0.39	0.61

* As the model is symmetric, equilibrium fraction of LCP price setters amongst Home exporters equals that of LCP price setters amongst importers from the Foreign country. Import price pass-through is measured in Home currency, and export price pass-through is defined in Foreign money. The two are equal in symmetric equilibrium

It can also be observed, that the presence of monetary rule shocks always implies higher pass-through than with productivity shocks. The reason is that productivity shocks have more indirect effects: they lower inflation, inducing some monetary easing, and at the same time increase consumption and decrease imports in both countries. Nominal exchange rate variance most probably increases and as the demand for imported intermediates drops, export revenues and profits also decline, while marginal costs become less exposed to exchange rate movements.

In contrast, monetary rule shocks have a direct impact on the nominal exchange rate, but have only second-order effects on prices through consumption demand. The exposure of marginal costs is more heavily lowered by productivity shocks than by monetary rule shocks. Thus, more exporters engage in LCP pricing, and pass-through is lower under productivity shocks.

Figure 1.7 Share of LCP-exporters and exchange rate pass-through (under baseline monetary policy)*



* As the model is symmetric, equilibrium fraction of LCP price setters amongst Home exporters equals that of LCP price setters amongst importers from the Foreign country. Import price pass-through is measured in Home currency, and export price pass-through is defined in Foreign money. The two are equal in symmetric equilibrium

1.6.1 Nominal wage rigidities and pass-through

According to *Figure 1.7*, the other important result is that nominal wage rigidities play a crucial role in pass-through and the choice of pricing policies. In all shock scenarios a robust picture emerges. If nominal wages are more flexible (with lower γ^w) in both countries, both export and import pass-throughs are lower. This statement remains robust across shocks and different scenarios for openness.and monetary reaction functions, as well (see later).

The reason is that firms have two degrees of freedom when accommodating to shocks: a standard one (through factor demands and price setting) and through a new channel, through the choice of pricing strategy. Relatively flexible labour market means wages are reacting relatively quickly. As a consequence, regardless of the nature of the shocks, nominal wages (and thus marginal costs) also vary quickly. Firms' costs will move faster towards the direction of the new equilibrium under relatively flexible wages. As a consequence, exporting firms' profits are more cushioned, and the cost of stabilising the price of their products in the export market's currency is lower. In turn, local currency pricing behaviour becomes more likely, and both the export and import price pass-throughs (in the respective market's currency) are lower.

This feature is in accordance with the second stylised fact outlined in *Section 1.2.4* that pass-through estimates and nominal wage rigidity are in a negative relationship. Models with exogenous price and wage stickiness (for example Ambler et al (2003)) were reluctant to explain why pass-through (to consumer prices) is generally lower if wages become more flexible.

In sum, the model of endogenous pass-through is more capable of matching the empirical fact outlined in *Section 1.2.4.*

It is worth mentioning, however, that due to the symmetric treatment of countries, this model can only explain lower pass-throughs if nominal wages are flexible in both counties. Therefore, the result and the empirical facts cannot be compared directly.[22]

1.6.2 Conduct of monetary policy and pass-through

The model replicates the *'beggar-thy-neighbour'* effect emphasised by Devereux et al (2004). Relatively stable monetary policy in one country always implies low (in this model zero) pass-through to import prices. Still, the model predicts that pass-through and inflation is in positive relationship outlined as in *Section 1.2.3*.

[22] One natural extension of the current model is to endogenise wage rigidities. In this case, depending on shocks firms would be able to optimise in three ways: through standard channels (factor demands and prices), the choice of currency and through the choice of how frequent wages were adjusted. Intuitively, the solution to this complex problem would depend on the labor share. The solution for equilibrium pass-through might take the form of corner solutions if labor share is sufficiently large. In this case, firms would be able to stabilise their profit exposures with small changes in wage-rigidity, and hence they would be more or less indifferent about which currency to hold prices fixed in advance. On the other hand, when labor share is sufficiently low, firms would not gain too much on changing the frequency of wage adjustment, and thus pass-through would take intermediate values more probably.

An alternative way of looking at the connection between inflation and pass-through in this model is to experiment with different monetary policy reaction functions. As demonstrated on *Figure 1.8* different monetary policies can end up with very different pass-throughs, if productivity shocks are dominant and wages are necessarily flexible.

In this case the presence of more *'inflationary hawkish'* central banks (those paying more attention to inflation than in the baseline calibration) creates a lower pass-through environment. On the contrary, if monetary policies are more prone to stabilize output than in the baseline set-up, pass-through increases. This can be also interpreted as a *'modified beggar-thy-neighbour''* effect.

These results are highly dependent on the shocks hitting the economy. The *'beggar-thy-neighbour'* effect can only be regarded as conditional: monetary policies more focusing on inflation might create a low pass-through environment under the presence of productivity shocks.

In the case of monetary rule shocks, different monetary rules end up with very similar pass-through coefficients. On the other hand, when productivity shocks are the source of uncertainty, the way how monetary policy is formulated makes a great deal if nominal wages are relatively flexible. Alternative rules give very similar pass-throughs if nominal wages are highly sticky.

For all monetary rules analysed, the result on the role of nominal wage rigidities remains valid. Higher wage stickiness leads to higher import price pass-through. Flexible labour markets makes firms easier to optimize by their factor demands and by their pricing policies, hence at the end, more exporting firms will choose LCP-pricing strategies.

The logic is, that high nominal wage stickiness implies low correlation of marginal costs with the nominal exchange rate: regardless of the conduct of monetary policy, exchange rate volatility will be the dominant factor when firms choose between pricing-strategies. In contrast, when wages are more flexible, the conduct of monetary policy matters significantly.

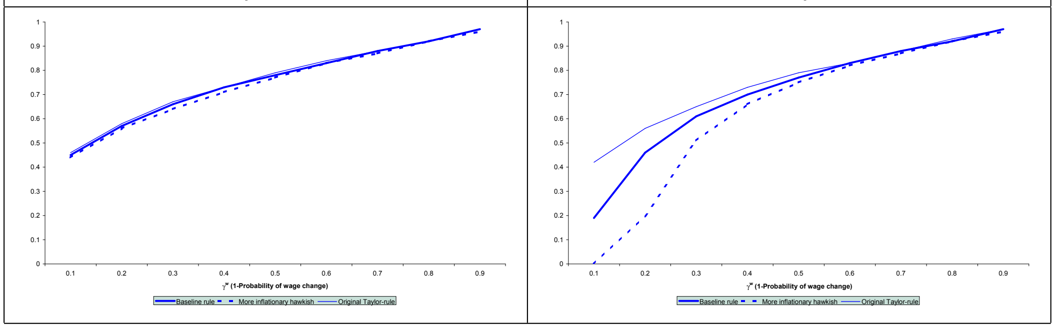
For example, under positive productivity shocks, a policy more biased towards controlling inflation will more likely decrease interest rates. In this case an exchange rate depreciation will occur together with a drop in marginal costs (due to the shock), while in the case with more weight to output stabilization the opposite happens (immediate exchange rate appreciation accompanied by decrease in costs). In turn, the correlation of costs with the exchange rate increases in the former case, while in the latter case, the correlation decreases. When nominal wages are flexible enough, this change in correlation becomes important.

In sum, numerical simulations of the model can generate a decline in pass-through associated with a change in the attitude of central banks shifting to focus more heavily on inflation. Endogenous currency choice can reinforce the argument put forward by Taylor (2000), that change in central bank policies contributes to lower pass-through. In addition, this can also confrom to the observation reported in *Section 1.2.1* to *1.2.3.* One should, however, bear in mind that the numerical simulations of the model presented here are only able to demonstrate this effect conditional on certain types of shocks hitting the economy.

Figure 1.8 Exchange rate pass-through under different parametrization of monetary policy rule*

Export/Import price pass-through
(with $\alpha = 0.5$)

Monetary rule shocks	Productivity shocks



1.6.3 No puzzle with respect to openness

As far as the effect of the intensity of foreign trade is concerned, the model suggest that for plausible values for nominal wage rigidity (γ_w higher than 0.3), more intense trade can even lower pass-through. Increasing openness creates an environment where costs are more correlated with the exchange rate. This naturally decreases pass-through as more firms are protected against exchange rate fluctuations (revenues and costs covary more). On the other hand, as the model is global, more openness implies higher demand for exports, so a larger share of firms will engage in exports. The greater role of exporting activities implies that the corporate sector as a whole will be more exposed to exchange rate fluctuations.

The two channels have opposite consequences for pass-through: the former reduces while the latter increases pass-through. Labour market rigidities are crucial in the net effects of the two contradicting forces. This trade-off does not have severe consequences for plausible nominal wage flexibility parameters. As γ_w higher than 0.3, the first effect dominates for all types of shocks and higher openness implies lower pass-through.

On the other hand, when wages are extremely flexible (γ_w lower than 0.3), higher openness raises pass-through. The logic is that with flexible wage setting firms are also able to optimise with their pass-through. Hence, greater openness makes marginal cost covary with the exchange rate to a lesser extent (because firms can optimise on pricing strategies), and there will be more room for PCP-price setting implying higher exchange rate pass-through. In the second case, the opposite happens: firms will be able to follow LCP-strategies without experiencing significant profit-losses.[23]

[23] The cut-off γ^w for which higher openness is required for higher pass-through will however be shock-dependent. It lies between 0.2 and 0.3. These cut-off values for γ^w are generally lower than what internationally macro estimates suggest.

Model simulations show that the possible puzzle coming out of intuition or from partial equilibrium models no longer holds if general equilibrium effects and the endogeneity of pass-through are taken into account, as well. Hence, according to numerical simulations there might not be a puzzle outlined in *Section 1.2.5* and openness and pass-through may not have trivial relationship.

1.7 Conclusions

There is an overwhelming evidence that exchange rate pass-through into consumer prices and import prices at the dock has declined in recent years in industrialised countries. There are however several explanations for this ranging from the behaviour of monetary policies to structural changes in the world economy. In addition, I report three stylised facts based on a collection of facts connecting the existing empirical literature on pass-through with that on the currency structure of trade and inflation.

First, I found that pass-through is closely related to the use of domestic currency in invoicing. Second, data also suggest that higher inflation usually corresponds with less role for domestic currency in invoicing. Third, pass-through and inflation seems to be in negative relationship.

In addition, though small sample size does not enable us to use sophisticated econometric techniques, there seems to be a positive relationship between nominal wage rigidity and pass-through. Finally, according to data, there is no clear relationship between openness and pass-through.

In order to explain the above stylised facts, I set up an extended version of the endogenous pass-through model of Devereux et al (2004). It seems that this model can explain the above mentioned observations. The model assumes that pass-through and the use of domestic currency in invoicing is negatively linked. This is a key assumption and it is consistent with the first stylised fact.

The robust finding comes out from numerical simulations is that flexible nominal wages generally imply lower pass-through. This is in line with the empirical observations reported.

It is also shown that the conduct of monetary policy (how much weight is devoted to inflation stabilisation) also matters in pass-through. The behaviour of monetary policy, however, alters pass-through markedly when nominal wages are relatively flexible and productivity shocks are the dominant source of uncertainty. The model can partly explain why a change in central bank attitude towards putting more focus on inflation stabilisation might imply a decrease in pass-through. Thus, model simulations also partly explain why inflation is in positive correlation with pass-through observed in the data.

Numerical simulations of this model shows that the role of openness in pass-through determination can take either directions. Increasing openness has two effects; and nominal wage rigidities determine whether they lead to higher or lower pass-through. Hence, this can give an explanation why empirical studies based on partial equilibrium models are reluctant to find significant role for openness in explaining pass-through.

Noting, that countries are handled identically and shocks are held idyosincratic in this model. Deeper examination of asymmetries between countries poses an interesting and challanging task for future research.

Chapter 2

2 Endogenous Exchange Rate Pass-through and Monetary Policy: the Role of Imported Intermediates and Country Size

2.1 Introduction

In this *Chapter* I turn my focus on how monetary policies should form policy if agents can change their pricing policies in open economies. A theoretical model with endogenous currency choice and imported intermediates was numerically simulated and compared to the baseline model of Devereux et al (2004) where imported intermediates play no role.

The conduct of optimal monetary policy is an interesting question in open economy macroeconomics. Dynamic general equilibrium open economy models with sticky prices and wages suggests that in closed economies welfare maximising (optimal) monetary policy should aim at keeping inflation at a low level, and for some instance it should also take care of the output gap or unemployment. In this way monetary policy can counteract the loss resulting from sticky prices or wages (see e.g. Woodford (2003), Erceg et al (2000) and Benigno and Woodford (2003)).

The optimal monetary policy problem in open economies, however, is not as straightforward as in closed economies. Domestic and foreign prices may deviate implying an additional relative price movement, and consequently, a deviation of output from the socially optimal (frictionless) one. Clarida, Gali and Gertler (2001) and Gali and Monacelli (2005) derives that for certain restrictive cases, notably, when only price rigidities are present and purchasing power parity holds and imports only consist of final consumption goods, monetary policy should aim to stabilise domestic prices. That is, optimal monetary policy in closed and open economies are isomorphic to the *'canonical'* closed economy model.

On the other side, according to Monacelli (2003) once exchange rate pass-through is imperfect, even under efficient productivity shocks monetary policy in open economies faces a short-run trade-off between stabilization of inflation and output gap. In addition, he also shows that the optimal monetary policy under commitment entails a smoothing of the deviation from the law-of-one price, as well.

However, in open economy models not only imperfect pass-through, but wage indexation may also introduce a deviation from the *canonical* closed economy model of optimal monetary policy. Campolmi (2006) argues that once wages are (at least partly) indexed to past CPI inflation, inward looking policies (focusing on purely the price changes of domestically produced goods) are no more optimal. She also approximates the optimal rule with a simple rule (among the Taylor-type rules) and the rule performing best is the one which consist of total

CPI and nominal wage inflation.[24]

Once, the strict assumptions of the open economy model of Clarida, Gali and Gertler (2001) are abandoned optimal monetary policy should no more purely focus on domestic inflation.

All the above mentioned studies, however, assume that price rigidities are exogenous and constant over time and states. In the model of Devereux et al. (2004) pass-through is endogenised. They proposes a new argument in favour of following *'inward-looking'* monetary policy (which stabilises only domestic inflation) in open economies. They show that if domestic monetary policy achieves stabilisation of domestic money growth rate, it encourages foreign exporters to set their prices in the respective market's currency (Local Currency Pricing). Hence, this would also dampen the pass-through into import prices, as well.

The endogeneity of exchange rate pass-through serves as an *'automatic stabiliser'*. Though not uniquely, this seems to conform to empirical studies of, for example, Choudri and Hakura (2006), Devereux and Yetman (2002), Taylor (2000) and Gagnon and Ihrig (2004) who found that countries with low and stable inflation rates have lower exchange rate pass-through.

Strictly speaking, this argument is not the usual exact solution to the optimal monetary policy problem: it highlights a channel pointing towards the optimality of *'inward looking'* policy. Inward looking policy is only optimal if no inefficient shocks are present in the economy. Indeed, in the model by Devereux et al (2004), only price and wage rigidities are present and the only source of uncertainty is money supply shocks. In such a restrictive case, intuitively, the *'inward looking'* policy is also the optimal one.

In other words, the model of Devereux et al (2004) only approximates 'optimal policy' in a crude manner. In this model low pass-through corresponds to optimal policy. What is the reason for this? In the *'canonical' New-Keynesian model* (with Calvo price setting) there are two welfare costs of price rigidities. The first is related to the fact that it implies fluctuation in the output gap (measured as the deviation from flexible price output) and the second one is due to price dispersion. However, in this type of model the only nominal friction in the economy is that all firms set price ex ante and one group of them has sticky in one currency, while the other group has sticky price in the foreign currency. Hence, optimal policy in this set up only aims to minimize the costs of this type of price dispersion. Therefore, optimal policy in this model is the one which creates low pass-through. Hence *'inward looking'* policy can be regarded as optimal if and only if only these type of frictions are present. Therefore, one should better think of it as an optimal policy if the central bank is only allowed to perform a strict inflation targeting regime with only inflation in its loss function in an economy with these types of nominal frictions.

The third crucial assumption in the model of Clarida, Gali and Gertler (2001) is that imports are treated as final consumption goods. What happens if this assumption is abandoned and imports are intermediates?

[24] The analytical derivation of optimal monetary policy in open economies is rather complicated. Világi (2004) shows in a small, open economy model that the loss function of the optimal monetary policy contains the real exchange rate, as well.

McCallum and Nelson (2001) argues that even if imported raw materials are used in production and pass-through is perfect for import prices, there is less of a contrast between controlling inflation in an open economy and controlling inflation in a closed economy.

On the other hand, according to Smets and Wouters (2002), in the case of imported intermediates and imperfect pass-through, a central bank that wants to minimise the resource costs of staggered price setting will aim at minimising a weighted average of domestic and import price inflation.

The question posed in this *Chapter* is whether the conclusions of Devereux et al (2004) still hold if imported intermediates are included in the production technology. In other words, the question is whether the endogenous pass-through model of Devereux et al (2004) amended by imported intermediates points back to the *'canonical'* model of closed economy or not. For this purpose, I extend the model of Devereux et al (2004) with imported intermediates in the simplest possible way: by a Leontieff-type production function. Under this technology the conditions on optimal pricing remains similar to the one in the model without imported intermediates.

Acording to numerical simulations of the model, once countries are of equal size and monetary policies are uncorrelated and equally stable, imported goods in the production function does not have numerically large effects on pass-through compared to the model without them. Letting the two countries differ in size, pass-throughs in both countries dramatically change. In the relatively small country export and import price pass-through turns out to be higher, though the latter depends on how intensely imported goods are used in production.

One should also emphasise, that the model in this Chapter only deals with monetary policies with exogenous policies (money growth targets with some noise). In this respect, the policy conclusions should be understood as referring to a rather restrictive class of policies. One further remark should also be made, that by introducing imported goods, neither new channels on the deviation from the flexible price output nor on price dispersion is built in. Therefore, optimal policy will again the one which creates low pass-through. So, again I only analyse how strict inflation targeter central banks should behave.

As far as the conduct of monetary policy is concerned, the main result is that the original conclusion of the model by Devereux et al (2004) remains intact even if country size and monetary policies are asymmetric.

The effects arising from the endogeneity of pass-through would be even stronger, and thus creating stable domestic monetary policy (as mentioned for a central bank following a strict inflation targeting policy) is even more important when imports serve as a factor of production regardless of country size.

Simulations also suggest that for relatively small countries the *'beggar-thy-neighbour'* effect is more pronounced and monetary policies are able to stabilise aggregate inflation easier with the help of endogenous changes in pass-through.

This chapter is organised as follows. In *Section2.2* the model is briefly outlined, while in *Section 2.3* results are discussed. Finally, *Section 2.4* concludes.

2.2 The model

The basic set-up of the model is quite similar to that of Devereux et al (2004) and to some extent the model outlined in *Chapter 1*. Hence, I only briefly summarise it and highlight the basic differences from it. There are two countries in which exporting firms choose between local currency pricing (LCP) or producer currency pricing (PCP) strategies. Home and Foreign countries constitute the world economy, and consequently, countries are not small, open economies, with each country's monetary policy also having an effect on either domestic or foreign inflation as well as on real economic developments.

The two country set-up is crucial in the feature of the model that a country with a relatively stable monetary policy induces firms to price in the national currency, leading to a drop in pass-through. The conclusion for optimal monetary policy, namely, that it should mostly focus on creating domestic monetary stability, is a result of the interaction of agents in both countries. This is one of the basic mechanisms of the endogeneity of exchange rate pass-through.

All prices and an exogenously set fraction of wages are assumed to be held fixed for one period in advance. This is a very strict nominal rigidity: all prices are predetermined for one period. As prices are predetermined, they are more sticky in the short run than in Calvo-type or Taylor-type price setting would generate. Prices, however can be adjusted after the shock occurs, and after the second period a new equilibrium is reached. Hence, in this model, unlike in the case of Calvo-type or Taylor-type pricing prices are flexible after the second period.

The flexibility of prices after 2 periods implies that the model has only a limited ability to explain price dynamics, and therefore I do not attempt to match the model with data . The relatively tight assumption of *ex ante* predetermined prices is required for deriving optimality conditions with regard to which pricing strategies are optimal, otherwise the problem would become too complicated.

The basic difference between this model and that of Devereux et al (2004) is that here imported intermediates also serve as a factor of production, though only in a simple manner. The first main difference between the model in this Chapter and that in Chapter 1 is that in order to be comparable to the model of Devereux et al (2004), monetary policy sets money supply and part of wages are predetermined (fixed) here. That is, not a New-Keynesian wage-Phillips curve is in place, but a simple set-up for rigidities imported from Devereux et al (2004). A fixed portion of wages are set ex ante and they are predetermined. The second departure point lies in the way monetary policy is modelled: in the model of Chapter 1 a Taylor-rule governs interest rate, in this Chapter monetary authorities set exogenous money supply growth rates. The choice of monetary policy was again chosen in order to be comparable to Devereux et al (2004).

As shown later, the presence of imported intermediates does not have very significant effects on the model's predictions when countries are identical in size. However, this is no longer valid if countries are heterogeneous in their monetary performance. Incorporating imported intermediates magnifies the stabilising role of the endogeneity of currency of pricing. Putting even more emphasis on controlling domestic inflation (for central banks pursuing strict inflation targeting) is more of a neccessity in smaller countries than in the case with identical countries.

2.2.1 Households' problem

Each consumer k in the Home country maximises expected lifetime utility with leisure, consumption and real money holdings in the utility function:

$$U_t(k) = E_t \sum_{s=t}^{\infty} \beta^{s-t} u_s(k) \tag{64}$$

where instantenous utility is separable:

$$u_s(k) = \frac{C_s(k)^{1-\rho}}{1-\rho} + \chi \ln(\frac{M_s(k)}{P}) - \frac{\eta}{1+\psi} L_s(k)^{1+\psi} \tag{65}$$

$C_s(k)$ denotes aggregate consumption, $\frac{M_s(k)}{P_s}$ refers to real money balance and $L_s(k)$ is labour supply at time s. ρ and χ measure the intertemporal elasticity of substitution, the weight of money holdings, respectively. Note that in contrast to the model in *Chapter 1*, there is a money-in-the-utility (MIU) setup. Disutility out of work depends on η and ψ. Households consume imperfectly substitutable Home and Foreign produced consumption goods and thus, aggregate consumption can be written as:

$$C(k) = \left[n^{1/\theta} C_h(k)^{\frac{\theta-1}{\theta}} + n^{1/\theta} C_f(k)^{\frac{\theta-1}{\theta}} \right]^{\frac{\theta}{\theta-1}}$$

where consumption of Home and Foreign goods is a composite of continuum of goods of n and $1-n$ goods, respectively. n stands for relative size of the Home country. θ is the elasticity of substitution between Home and Foreign goods.

Sub-aggregates of consumption are also used later. Similarily to the model in *Chapter 1* the definition of the consumption of Home produced goods by Home consumers and Foreign produced (imported) goods as

$$C_h(k) = \left[n^{-1/\lambda} \int_0^n C_h(i)^{\frac{\lambda-1}{\lambda}} di \right]^{\frac{\lambda}{\lambda-1}},$$

and

$$C_f(k) = \left[(1-n)^{-1/\lambda} \int_n^1 C_f(i)^{\frac{\lambda-1}{\lambda}} di \right]^{\frac{\lambda}{\lambda-1}},$$

respectively.

λ refers to the elasticity of substition between different varieties and it is assumed to be identical in both countries. Home consumer price index (minimum cost of acquiring 1 unit of aggregate consumption) can then be defined as

$$P_t = \left[n {P_{ht}}^{1-\theta} + (1-n) {P_{ft}}^{1-\theta} \right]^{\frac{1}{1-\theta}},$$

where P_{ht} and P_{ft} are the price index of Home and Foreign goods sold in the Home country, respectively. It is assumed that all prices are predetermined and set one period in advance. Further, it is also naturally assumed that all goods sold at Home has predetermined prices in Home currency. Exported goods can have two different prices (in symmetrical equilibrium and in the long run these two prices should be equalized). Fraction z (z^*) of Home (Foreign) goods are priced with Local Currency Pricing (LCP) abroad (at Home). As shown later, z and z^* are endogenously dependent on the model's properties and determined by the choice of (exporting) firms. The price index of Foreign (imported) goods sold at Home is a aggregate of LCP-priced and PCP priced goods.

$$P_{ft} = \left[\frac{1}{1-n} \int_{n}^{n+(1-z^*)(1-n)} (S_t P^*_{fht}(i))^{1-\lambda} di + \frac{1}{1-n} \int_{n+(1-z^*)(1-n)}^{1} P_{fht}(i)^{1-\lambda} di \right]^{\frac{1}{1-\lambda}},$$

where $P^*_{fht}(i)$ and $P_{fht}(i)$ refers to the Foreign and Home currency price of Foreign goods sold at Home, respectively.

Short term pass-through is highly related to the fraction z^*. A zero value of z^* implies full pass-through to imported goods and a value of 1 creates zero short term pass-through calculated in Home currency. Symmetrically, z is linked to the import price pass-through in the Foreign country (pass-through to Home produced exported goods in foreign currency). Incomplete risk sharing is also assumed, and households are only allowed to trade non-contingent nominal bonds.

Budget constraint connects current consumption and accumulation of nominal bonds (B_t) to labour income ($W_t L_t$) and profits (Π_t) plus the revenues earned on assets aquired in the past period ($(1 + r_{t-1})B_{t-1}$) where r_t is the yield of nominal bond. Home firm are only owned by Home consumers. The budget constriant for Home households is then:

$$P_t C_t + B_t = (1 + r_{t-1})B_{t-1} + W_t L_t + \Pi_t \tag{66}$$

Profits are total revenues minus wage costs and purchases of intermediate imported goods. Due to the fact that world economy consist of two countries, bond holdings (net foreign asset position) of Home households is equal to net foreign borrowing of Foreign households ($B^*_t = -B_t/S_t$).

Demands for individual varieties can be easily determined from a usual relationship. Demand for Home produced goods by Home consumers is:

$$C_{H,t} = n \left[\frac{P_{H,t}}{P_t} \right]^{-\theta} C_t,$$

and demand for Foreign produced goods by Foreign consumers is

$$C^*_{F,t} = (1-n)\left[\frac{P^*_{F,t}}{P^*_t}\right]^{-\theta} C^*_t.$$

In symmetric equilibrium each variety has the same price and thus imported consumer goods can be categorized into four categories, an LCP-priced, a PCP-priced Foreign good consumed by Home households, and an LCP-priced, a PCP-priced Home good consumed by Foreign households. Demand for PCP-priced Home goods sold in Foreing country is

$$C^*_{H,PCP,t} = n\left[\frac{S_t P^*_{F,PCP,t}}{P_{F,t}}\right]^{-\lambda}\left[\frac{P_{F,t}}{P_t}\right]^{-\theta} C_t.$$

The demand for LCP-priced Home goods sold in Foreign country is

$$C^*_{H,LCP,t} = n\left[\frac{P_{F,LCP,t}}{P_{F,t}}\right]^{-\lambda}\left[\frac{P_{F,t}}{P_t}\right]^{-\theta} C_t.$$

Demand for PCP-priced Home goods sold in Foreign country is

$$C^*_{H,PCP,t} = (1-n)\left[\frac{P_{H,PCP,t}}{S_t P^*_{H,t}}\right]^{-\lambda}\left[\frac{P^*_{H,t}}{P^*_t}\right]^{-\theta} C^*_t.$$

Finally,demand for LCP-priced Home goods sold in Foreign country is

$$C^*_{H,LCP,t} = (1-n)\left[\frac{P^*_{H,LCP,t}}{P^*_{H,t}}\right]^{-\lambda}\left[\frac{P^*_{ht}}{P^*_t}\right]^{-\theta} C^*_t.$$

Price sub-indices in the symmetric equilibrium have again the usual forms. Home consumer price index is

$$P_t = \left[nP_{ht}^{1-\theta} + (1-n){P_{ft}}^{1-\theta}\right]^{\frac{1}{1-\theta}},$$

import price index in the Home country is

$$P_{ft} = \left[(1-z^*)(S_t P^*_{fht})^{1-\lambda} + z^* {P_{fht}}^{1-\lambda}\right]^{\frac{1}{1-\lambda}}.$$

Foreign consumer price index is analogously

$$P^*_t = \left[n{P^*_{ht}}^{1-\theta} + (1-n){P^*_{ft}}^{1-\theta}\right]^{\frac{1}{1-\theta}},$$

and Foreign Import price index has the form of

$$P^*_{ft} = \left[z{P^*_{hft}}^{1-\lambda} + (1-z)(\frac{P_{hft}}{S_t})^{1-\lambda}\right]^{\frac{1}{1-\lambda}}.$$

Each household supplies one unit of differentiated labour. Households act as monopolists for each variaties of labour. Therefore, labour supply is determined by also taking labour demand into account. Elasticity of substitution between differentiated types of labour is ω. Optimality conditions imply that real wages are a wage mark-up times marginal rate of substitution between leisure and consumption.[25] Wage mark-up depends on the elasticity of substitution between different types of labour.

$$\frac{W_t(k)}{P_t} = \frac{\omega}{\omega - 1} \frac{E_t(U_l(..))}{E_t(U_c(..))} \tag{67}$$

Except for the Money-in-the-utility-setup, so far the model was the same to that in *Chapter 1.* Wage stickiness is now introduced here in a different way: with Taylor-type contracts. In symmetric equilibrium all types of labour has the same wage except that there remains a distinction between different types of labour with repsect to when wages are determined: the two categories are households with fixed (predetermined) and flexible wages. Supersript f and a stands for workers with one-period ahead predetermined (*fixed*) and adjustable (*flexible*) wages, respectively.After substituting for the utility function nominal wage of workers which can adjust their wage flexibly:

$$W_t^a = \frac{\omega\eta}{\omega - 1} P_t C_t^{\rho} (L_t^a)^{\psi} \tag{68}$$

and of those which have predetermined wages (for one period in advance):

$$W_t^f = \frac{\omega\eta}{\omega - 1} \frac{E_{t-1}((L_t^f)^{1+\psi})}{E_{t-1}(\frac{L_t^f}{P_t C_t^{\rho}})} \tag{69}$$

Denote the share of workers with adjustable wages by υ, aggregate wage index as:

$$W_t = \left[\upsilon (W_t^a)^{1-\omega} + (1-\upsilon)(W_t^f)^{1-\omega} \right]^{\frac{1}{1-\omega}}$$

Money demand can be derived from the first order conditions of utility maximisation together with the Budget Constraint.

$$\frac{M_t}{P_t} = \chi C_t^{\rho} \frac{1 + r_{t+1}}{r_{t+1}} \tag{70}$$

$$P_t C_t + M_t + B_t = (1 + r_{t-1}) B_{t-1} + M_{t-1} + W_t L_t + \Pi_t \tag{71}$$

where Π_t denotes total profits of all Home firms. Money supply is assumed to follow a random walk in logarithms: $m_{t+1} = m_t + u_{t+1}$. u_{t+1} is a monetary disturbance term with $E_t(u_{t+1}) = 0$ and variance of σ_u^2.[26]

[25] In the case of perfect competition in the labour market, the mark-up is one, which leads to a standard labour supply equation equating real wages with marginal rate of substitution between leisure and consumption.

[26] $m_t = \ln(M_t)$

Households' intertemporal choice is governed by the Euler-condition:

$$\frac{C_t^{-\rho}}{P_t} = \beta(1 + r_{t+1})E_t(\frac{C_{t+1}^{-\rho}}{P_{t+1}}) \tag{72}$$

The discount factor should be equal to the (nominal) yield of saving one marginal unit of consumption. The discount factor is thus, stochastic and at time $t-1$ it's value is:

$$d_{t-1} = \beta \frac{C_{t-1}^{\rho} P_{t-1}}{C_t^{\rho} P_t} \tag{73}$$

It is worth mentioning that so far the model is similar to that of Devereux et al (2004).

2.2.2 Production and factor demands

The first departure point from the the model of Devereux et al (2004) is inserting imported intermediate goods into the production side. A simple Leontieff-technology combines labour ($L_t(i)$) and imported intermediate inputs ($I_t(i)$). Note, that here I use the simple technology also incorporated in *Chapter 1's* model. Each firm uses all types of workers. Production function of firm i in the Home country is then:

$$Y_t(i) = \min(\frac{L_t(i)}{\alpha}, \frac{I_t(i)}{1-\alpha})$$

with a differentiated labour input of n types of labour.

$$L_t(i) = \left[\frac{1}{n} \int_0^n L_t(i,k)^{1-\frac{1}{\omega}} dk \right]^{\frac{1}{1-\frac{1}{\omega}}}$$

Wage indices can then be determined by

$$W_t = \left[(\frac{1}{n})^{\frac{1}{\omega}} \int_0^n W_t(k)^{1-\omega} dk \right]^{\frac{1}{1-\omega}}$$

given the distribution of wages ($W(k)$). The specification of the production function enables us to separate the problem for first solving for the aggregate demand for labour and imported intermediates, and then determine individual labour demands.The Leontieff-type production function was chosen, beacuse it is assumed that imports are rather complements than substitutes for labour. Moreover, in this model, substitution between the two factors would create computational problems. Except fot the Leontieff-prodution function case, the currency choice and the other part of the model would not be separable. This type of production function was also chosen by e.g. Smets and Wouters (2002) and McCallum and Nelson (2001).[27]

Given our assumption on technology, demand for aggregate labour and for imported intermediates is simply proportional to output ($L(i) = \alpha Y(i)$ and $I(i) = (1-\alpha)Y(i)$).The individual demands (of the *ith* firm) for labour of type k is:

$$L_t(i,k) = \left[\frac{W_t(k)}{W_t}\right]^{-\omega} L_t(i)$$

Marginal cost is simple a weighted arithmetic average of wages and import costs.

$$MC_t = \left[\alpha W_t + (1-\alpha)P_t^i\right] \tag{74}$$

The demand for labour with flexible and fixed wages can then be articulate as:

$$L_t^a = \upsilon L_t(\frac{W_t^a}{W_t})^{-\omega} = \alpha\upsilon(\frac{W_t^a}{W_t})^{-\omega} Y_t \tag{75}$$

$$L_t^f = (1-\upsilon) L_t(\frac{W_t^f}{W_t})^{-\omega} = \alpha(1-\upsilon)(\frac{W_t^f}{W_t})^{-\omega} Y_t \tag{76}$$

For simplicity I assume that prices of imported intermediates are equal to that of imported consumer goods. The reason is that with Leontieff-technology, relative import prices do not affect factor demands directly, and pricing policies of firms (at the their level) do not depend on their import decisions. Though, through general equilibrium channels, marginal costs, prices and the demand for imports are influenced indirectly.

2.2.3 Price setting

The derivation of optimal pricing policies (for given wages) is exactly the same as in *Chapter 1*. Firms have the monopoly power of setting price, but it is assumed that all prices are set ex ante in period $t-1$. Firms determine prices as an expected marginal costs times a markup. In the symmetric equilibrium there will be six different prices. Two types of prices has the traditional pricing formula with monopolistically competitive markets. Home produced consumer goods priced in Home currency is $P_{H,t} = \frac{\lambda}{\lambda-1}E_{t-1}MC_t$, while the price of Foreign consumer goods in Foreign currency is $P_{F,t}^* = \frac{\lambda}{\lambda-1}E_{t-1}MC_t^*$.

For exported goods prices the choice of currency also matter in firms' decisions. Home exporters face a demand curve:

$$D(P_t(i)) = (\frac{P_t(i)}{P_{H,t}^*})^{-\lambda}(\frac{P_{H,t}^*}{P_t^*})^{-\theta} C_t^* + (1-\alpha)Y_t^* \tag{77}$$

[27] A fruitful departure point would be to insert a more flexible production technology (e.g. CES-type) into the model. A possible way to enable a more general production function would be to insert a competetive sector which produces an aggregate good out of the many differentiated goods. Then it sells the aggregate good either to consumers or to producers. Thus the elasticity of final demand would play no role in the pricing decision.

The first part refers to the demand for Home produced consumer goods purchased by Foreign consumers, the second part describes the demand for intermediate imported goods of the Foreign economy. (For simplicity I define the individual price ($P_t(i)$) denominated in foreign currency.) Firms optimize between different pricing policies by comparing expected profits. Expected profit under PCP pricing is:

$$E_{t-1}(\pi_t^{PCP}) = E_{t-1}\left[d_{t-1}\left\{P_t^{PCP}(i) - MC_t(i)\right\}\left\{\left[\frac{P_t^{PCP}(i)}{S_t P_{H,t}^*}\right]^{-\lambda}\left[\frac{P_{H,t}^*}{P_t^*}\right]^{-\theta} C_t^* + (1-\alpha)Y_t^*\right\}\right] \tag{78}$$

While in the case of LCP pricing stategies expected profits are:

$$E_{t-1}(\pi_t^{LCP}) = E_{t-1}\left[d_{t-1}\left\{S_t P_t^{LCP}(i) - MC_t(i)\right\}\left\{\left[\frac{P_t^{LCP}(i)}{P_{H,t}^*}\right]^{-\lambda}\left[\frac{P_{H,t}^*}{P_t^*}\right]^{-\theta} C_t^* + (1-\alpha)Y_t^*\right\}\right] \tag{79}$$

In order to compare profits optimal prices for any given pricing policies should be determined. Now take the advantage of Leontieff-technology that makes pricing problem separable with respect to consumer and imported intermediate goods. As demand for imported intermediates does not depend on the firm's individual price, but it is a fixed ratio of foreign production, optimal price of consumed exported goods has the same form as without imported intermediates. Optimal price of LCP priced consumer goods is then:

$$P_{H,LCP,t}^* = \frac{\lambda}{\lambda-1}\frac{E_{t-1}(MC_t S_t^\lambda A_t)}{E_{t-1}(S_t^\lambda A)} \tag{80}$$

While in the case of PCP-strategy optimal price takes the form of:

$$P_{H,PCP,t}^* = \frac{\lambda}{\lambda-1}\frac{E_{t-1}(MC_t A_t)}{E_{t-1}(S_t A_t)} \tag{81}$$

where A_t denotes all predetermined variables ($A_t = d_{t-1}(P_{H,t}^*)^{\lambda-\theta}C_t^*$). Profits under different pricing policies are then:

$$E_{t-1}(\pi_t^{PCP}) = \Omega\left[E_{t-1}(S_t^\lambda A_t)\right]^\lambda\left[E_{t-1}(S_t^\lambda MC_t A_t)\right]^{1-\lambda} \tag{82}$$

and

$$E_{t-1}(\pi_t^{LCP}) = \Omega\left[E_{t-1}(S_t A_t)\right]^\lambda\left[E_{t-1}(MC_t A_t)\right]^{1-\lambda} \tag{83}$$

where $\Omega = \frac{1}{\lambda-1}(\frac{\lambda}{\lambda-1})^{-\lambda}$.

After a second-order Taylor approximation one can arrive at the necessary and sufficient condition for using PCP pricing. Firms choose LCP strategies in the Home country if

$$\frac{var_{t-1}(s_t)}{2} - cov_{t-1}(s_t, mc_t) < 0 \tag{84}$$

where lowercase letters stand for logarithms of the original variables. Home firms will choose PCP pricing, when (1) the nominal exchange rate is highly volatile, or when (2) wages and the costs of imported intermediates are highly correlated with the nominal exchange rate. The condition highlights that the Home firm is more likely to choose LCP pricing when it is "naturally" hedged against exchange rate fluctuations, i.e. the correlation of costs with the nominal exchange rate compensates for the volatility in the revenues (determined by nominal exchange rate fluctuations). In this case, the mark-up of the firm will accommodate such that it compensates for the gains and losses resulting from exchange rate fluctuations.

From this condition one can conclude that there are two mechanisms affecting the choice of currency: the decision depends on the volatility of the nominal exchange rate; the more volatile the nominal exchange rate, the more incentive to choose PCP-strategy. LCP strategy is preferred when the firm is naturally hedged against exchange rate fluctuations. For Foreign firms the condition for deciding between different pricing policies can also be derived, the only difference is that here nominal exchange rate fluctuations affect firms' profits in the opposite direction, so the sign of the marginal cost term becomes positive. Foreign firm will choose LCP policy if

$$\frac{var_{t-1}(s_t)}{2} + cov_{t-1}(s_t, mc_t^*) < 0 \tag{85}$$

Note that these conditions when firms choose local currency or producer currency pricing are exactly the same as in *Chapter 1*. The determination of the equilibrium pass-through is also similar. Hence, I only briefly explain how equilibrium pass-through is determined.

There are again three types of equilibria: two under pure strategies and one under mixed strategy with probabilities of choosing LCP are z and z^*.

If for any possible values of z and z^* the two inequalities hold, then all firms will opt for LCP regardless of other firms' behaviour. In contrast, when for all pairs of z and z^* the opposite of the conditions hold, then all firms will engage in PCP strategy whatever other firms have chosen. In these cases the equilibria under pure strategies are stable.

If equilibria under pure strategies are not stable, there can still be equilibrium under mixed strategies.[28] The mixed strategy can be described as domestic firms choose LCP price with probability z and Foreign firms with probability z^*. Equilibrium mixed strategies are those for which the two conditions on choosing LCP hold exactly as equalities.

To find numerically the equilibria I used a grid search algorithm. For any values of z and z^* the model is solved and then I determine z and z^* for which the two conditions are equalities. As a second step, the stability of any solution (whether any firm has an incentive to deviate) should be checked.

[28] Devereux et al (2004) was able to derive the mixed strategy equilibria analytically. Here, due to the complexity created by imported intermediates, only numerical solutions are demonstrated.

Again, the above formulas are analogous to that of Gopinath et al (2007) where optimal currency choice is modelled by dynamic price setting with Bellman-equations.

2.2.4 Market clearing and the current account

Domestic consumption equals sales of Home goods sold at Home plus Foreign consumer goods imported by Foreign LCP-exporters and that of Foreign PCP-exporters. Total domestic production incorporates domestically sold consumer goods plus exported consumption goods and exported intermediate goods.

$$Y_t = C_{H,t} + I_t^* + (1-z)C_{H,PCP,t}^* + zC_{H,LCP,t}^* \tag{86}$$

$$Y_t^* = C_{F,t}^* + I_t + (1-z^*)C_{F,PCP,t} + z^*C_{F,LCP,t} \tag{87}$$

Current account clears in equilibrium, hence trade balance plus foreign interest income should equal to change in net foreign assets:

$$\begin{aligned} P_tC_t + B_{t+1} = (1+r_{t-1})B_t + P_{H,t}C_{H,t} + zP_{H,LCP,t}C_{H,LCP,t}^* + \\ +(1-z)P_{H,PCP,t}C_{H,PCP,t}^* + S_tP_{H,t}^*I_t^* - P_{F,t}I_t \end{aligned} \tag{88}$$

and the profit of domestic firms' is:

$$\begin{aligned} \Pi_t = P_{H,t}C_{H,t} + zP_{H,LCP,t}C_{H,LCP,t}^* + (1-z)P_{H,PCP,t}C_{H,PCP,t}^* + \\ +S_tP_{H,t}^*I_t^* - P_{F,t}I_t - W_tL_t \end{aligned} \tag{89}$$

2.2.5 Model solution

In the model without imported intermediates one can arrive at a closed-form solution to nominal exchange rate determination. For simplicity, however, I do not derive a closed-form but a numerical solution of the model. Numerical solution proceeds as follows. I first linearly approximate the model around its nonstochastic steady state when all prices and wages are equal. Let denote $\hat{x}_t = \ln X_t - \ln X^{SS}$ as the log deviation of variable x from its steady state value (X^{SS}). The six pricing equations and the price indices can in deviations from the steady state are then:

$$\hat{p}_t = n\hat{p}_{ht} + (1-n)\hat{p}_{ft} \tag{90}$$

$$\hat{p}_t^* = n\hat{p}_{ht}^* + (1-n)\hat{p}_{ft}^* \tag{91}$$

$$\hat{p}_{ht} = E_{t-1}\widehat{mc}_t \tag{92}$$

$$\hat{p}_{ht}^* = z\hat{p}_{H,LCP,t}^* + (1-z)(\hat{p}_{H,PCP,t} - \hat{s}_t) \tag{93}$$

$$\hat{p}_{ft} = (1-z^*)(\widehat{s}_t + \hat{p}_{F,PCP,t}^*) + z^*\hat{p}_{F,LCP,t} \tag{94}$$

$$\hat{p}^*_{H,LCP,t} = E_{t-1}\widehat{mc}_t - E_{t-1}s_t \quad (95)$$

$$\hat{p}_{H,PCP,t} = E_{t-1}\widehat{mc}_t \quad (96)$$

$$\hat{p}^*_{F,LCP,t} = E_{t-1}\widehat{mc}^*_t + E_{t-1}s_t \quad (97)$$

$$\hat{p}^*_{F,PCP,t} = E_{t-1}\widehat{mc}^*_t \quad (98)$$

and

$$\widehat{mc}^*_t = \alpha\widehat{w}^*_t + (1-\alpha)p^*_{ht}$$

$$\widehat{mc}_t = \alpha\widehat{w}_t + (1-\alpha)p_{ft}$$

One can then derive the price index of imported consumer goods[29].

$$\begin{aligned} \widehat{p}_{ft} \quad &= \quad \frac{1}{1-(1-\alpha)^2}(\alpha E_{t-1}\widehat{w}^*_t + (1-\alpha)\alpha E_{t-1}\widehat{w}_t + \\ &\quad +(z^* - (1-\alpha))E_{t-1}\widehat{s}_t + (1-z^*)\widehat{s}_t) \end{aligned}$$

The differentials of consumer price indices can be calculated and this is exactly the same as the one without imported intermediates.

$$p_t - p^*_t = (1 - nz - z^*(1-n))s_t \quad (99)$$

Hence, the presence of imported goods does not change relative prices. (99) shows that relative consumer prices can only move with fluctuations in the nominal exchange rate. Linearising money demand functions and its corresponding Foreign version one can yield a simple relationship:

$$c_t = \frac{m_t - p_t}{\rho} \quad (100)$$

$$c^*_t = \frac{m^*_t - p^*_t}{\rho} \quad (101)$$

From (100) and (101) relative consumptions can also be written as:

$$c_t - c^*_t = \frac{m_t - m^*_t}{\rho} - \frac{1 - nz - z^*(1-n)}{\rho}s_t \quad (102)$$

This is again the same as in the model without imported intermediates. Hence, the presence of imported intermediates does not affect the determination of relative consumption (though it has implications for Home and Foreign consumption *levels*, but not on their differences). When there is a full pass-through ($z = z^* = 0$), PPP holds and (102) represents a *'standard'* monetary model of the exchange rate. Exchange rate fluctuations have an expenditure-switching

[29] Note that in Chapter 1's model we did not analytically solve for prices. Here we have a simpler structure and we can successfully solve for prices and the nominal exchange rate.

effect by modifying the composition of world consumption. Linearising the balance-of-payments condition and using pricing equations together with demand schedules one arrives at:

$$d\widehat{B}_{t+1} = \alpha_c \overline{PC}(-\alpha_c \widehat{c}_{Ht} + (1+r_t)\widehat{dB}_t/\alpha_c \overline{PC} + \alpha_c n \widehat{c}_{Ht}$$
$$+\alpha_c n(1-\theta)(\widehat{p}_{ht} - \widehat{p}_t) + +\alpha_c(1-n)z((1-\lambda)(\widehat{p}^*_{H,LCP,t} - \widehat{p}^*_{ht})$$
$$+(1-\theta)(\widehat{p}^*_{ht} - \widehat{p}^*_t) + \widehat{p}^*_t + \widehat{s}_t - \widehat{p}_t + \widehat{c}^*_t)+$$
$$+\alpha_c(1-n)(1-z)((1-\lambda)(\widehat{p}_{H,PCP,t} - \widehat{s}_t - \widehat{p}^*_h) \tag{103}$$

Where α_c, $\overline{P}$, $\overline{C}$ denote steady share of consumption, price level and consumption level, respectively. $\widehat{db}_{t+1}$ refers to percentage point deviation of net foreign assets to its steady state level.

Log-linearization production yields:

$$\widehat{y}_t = +\alpha_c n \widehat{c}_t - \alpha_c n\theta(\widehat{p}_{ht} - \widehat{p}_t) + \alpha_c(1-n)z((1-\lambda)(\widehat{p}^*_{H,LCP,t} - \widehat{p}^*_{ht})$$

$$-\theta(\widehat{p}^*_{ht} - \widehat{p}^*_t) + \widehat{c}^*_t) + +\alpha_c(1-n)(1-z)((1-\lambda)(\widehat{p}_{H,PCP,t} - \widehat{s}_t - \widehat{p}^*_h)$$
$$-\theta(\widehat{p}^*_{ht} - \widehat{p}^*_t) + \widehat{c}^*_t) + \alpha_i(1-n)\widehat{i}^*_t \tag{104}$$

with α_i referring to steady state import share.

Linearisation of Euler-conditions yields:

$$\widehat{p}_t + \rho\widehat{c}_t = E_t(\widehat{p}_{t+1} + \rho\widehat{c}_{t+1}) \tag{105}$$

$$\widehat{p}^*_t + \rho\widehat{c}^*_t = E_t(\widehat{p}^*_{t+1} + \rho\widehat{c}^*_{t+1}) \tag{106}$$

As $(1-\upsilon)$ part of wages are fixed in both countries, log-deviation of aggregate wage to steady state is:

$$\widehat{w}_t = \nu\widehat{w}^a_t + (1-\nu)\widehat{w}^f_t \tag{107}$$

Further, by using Euler conditions flexible (adjustable) wages can then be described as:

$$\widehat{w}^a_t = \widehat{p}_t + \rho\widehat{c}_t + \psi\widehat{l}^a_t \tag{108}$$

While fixed (predetermined) wages are determined by expected future consumption, leisure and prices:

$$\widehat{w}^f_t = E_{t-1}\widehat{p}_t + \rho E_{t-1}\widehat{c}_t + \psi E_{t-1}\widehat{l}^f_t \tag{109}$$

Labour demand for labour with flexible wages:

$$\widehat{l}^a_t = -\omega(\widehat{w}^a_t - \widehat{w}_t) + \widehat{y}_t \tag{110}$$

and demand for labour with predetermined wages:

$$\widehat{l}^f_t = -\omega(\widehat{w}^f_t - \widehat{w}_t) + \widehat{y}_t \tag{111}$$

As a next step, one can find a formula for the evolution of nominal exchange rate[30]:

$$s_t = \frac{c_t - c_t^* + \frac{d\widehat{B}_{t+1}}{\alpha_c \overline{PC}}}{\Gamma} \tag{112}$$

Nominal exchange rate is linked to relative consumption, net foreign asset position and on the fraction of LCP price setters in both countries and on the share of imported intermediates. During the numerical simulations the fraction of LCP price setters were changed by grid search and the solution was so that marginal firms were indifferent between pricing strategies, i.e. the conditions on price setting were fulfilled as equlity.

2.3 Calibration

Several simulation exercises are performed with regards to country size, monetary variances and the share of imported intermediates. In all cases monetary shocks are set uncorrelated. All other coefficients of the model are kept unchanged across the scenarios. Elasticity of substitution between different types of labour (ω) and between Home and Foreign consumer goods (θ) is set similarily to Devereux et al (2004) as 1.5. The share of labour with fixed wages (ν) is imported from Devereux et al (2004) at.0.75. In each period three quarters of workers have fixed wages. This parameter is key in ensuring inner solutions of the model. For example, a value of 0.5 would result in corner solutions even in the case with symmetric monetary policies. Elasticity of intertemporal substitution (ρ) is calibrated to 1.25 and utility function was assumed to be log-linear with $\psi = 1$ (these values are also kept at the same value as in the model without imported intermediates). Steady state interest rate has a value of 0.1 annually. Steady state level of consumption ($\overline{C}$) and consumer prices ($\overline{P}$) are both set as 1[31]. The choice of λ is so that steady state markup was 25 per cent ($\lambda = 5$). *Table 2.1* summarises the parameter values for all the simulations performed.

[30] where

$$\Gamma = zn + z^*(1-n) + (\theta-1)n(1-z^*)\frac{\alpha}{1-(1-\alpha)^2} - (\theta-1)(1-n)\alpha z + n\frac{\alpha}{1-(1-\alpha)^2} + (\theta-1)(1-n)\alpha$$

[31] These parameters only serve as a numeraire, hence the resulting optimal shares of LCP and PCP price-setters were not affected by them.

Table 2.1 Calibrated parameters in different scenarios

Parameter	Equal countries		Small Home country	
	scenario			
	Equal	More stable	Equal	More stable
	Home monetary policy		Home monetary policy	
α	$0.1, 0.2..., 0.9, 1$	$0.5, 0.75, 0.9, 1$	$0.5, 0.75, 1$	$0.5, 0.75, 0.9, 1$
σ_m^2	1	$0.6, 0.7.., 0.9, 1$	1	$0.6, 0.7.., 0.9, 1$
n	0.5		0.3	
θ	1.5			
ω	1.5			
$(\sigma_m^*)^2$	1			
ρ	1.25			
r	0.1			
λ	5			
υ	0.75			
ψ	1			

2.4 Results

In this model pass-through is directly linked to the share of exporting and importing firms choosing LCP or PCP pricing policies. Firms do not observe monetary shocks before choosing pricing policies. When monetary shocks are realised, the foreign currency price of exporting firms with PCP strategies is renominated by the change in the nominal exchange rate. Firms with LCP strategies hold their price in foreign currency fixed, and their profits are higher or lower depending on the direction of nominal exchange rate movements. What matters in pass-through here is monetary policy shocks. The nature of monetary policy shocks, together with the pricing policies of firms, determines the volatility of the nominal exchange rate and its covariance with marginal costs. Firms are more likely to choose LCP strategies when exchange rate volatility is low, so their profits are not significantly affected by monetary disturbances.

On the other hand, the probability of choosing LCP strategy is higher if firms' costs co-moved with the nominal exchange rate. In the case of significant covariance between marginal costs and the nominal exchange rate, firms' profits are cushioned from the evolution of the nominal exchange rate, as their revenues and costs are more likely to move in the same direction. Pass-through becomes an endogenous feature of the economy: nominal exchange rate volatility and its covariance depend on the share of LCP price setters and *vice versa.*

The model enables us to analyse the role of imported intermediates in a model with endogenous determination of exchange rate pass-through. As it became evident in the theoretical derivation, imported intermediates modify the behaviour in our economy in two ways.

First, the higher their share in production is, the higher the demand is for exported goods. Hence, the more intensively imported intermediates used in production, the higher the share of firms' revenues is exposed to exchange rate risks. This alone might lead to lower probability of choosing LCP pricing, because it becomes more difficult to counteract exchange rate movements.

Second, introducing imported intermediates increases the dependence of firms' costs on exchange rate movements, as they constitute an important part of production costs. In turn, a higher share of intermediates creates a situation where firms' profits are less exposed to exchange rate fluctuations.

The two channels work in the opposite direction, and equilibrium pass-through depends on the relative importance of the two channels outlined above.

The role of country size can also be analysed in this model. I perform two scenarios, one with equal country sizes and one with assuming that Home country is small ($n = 0.3$). It turns out that country size, together with imported intermediates, can significantly change the picture even under symmetric monetary policies.

The second set of my results deals with the case of asymmetric monetary policies. In this respect, simulations show how a fall in Home monetary variance affects pass-through. The robust picture holds with and without imported intermediates. An increase in Home monetary stability always induces a drop in import pass-through and a rise in export pass-through. The inclusion of imported intermediates magnifies this effect.

As mentioned before, a more general production function could have inserted via a competetive sector which sells the aggregate good either to consumers or to producers. Intuitively, in this set up firms would accomodate to shock more easier with their factor demands. The first (the traditional adjustment) channel would then be stronger. This implies that the need for changing the currency of pricing would be less of a necessity for firms. All results might remain quantitatively similar, though corner solutions would be less likely and pass-through will possible not so sensitive to country size and openness.

2.4.1 Symmetric monetary policies and identical countries

The first exercise shows the pure effect of the introduction of imported intermediates into the endogenous pass-through model. As mentioned above, intermediates affect pass-through in two ways. The first one works through the higher exposure of total export revenues and the second one through their effect on marginal costs.

Scenarios differed only in the labour share (one minus the share of imported intermediates) used. Labour share was set between 0.1 and 1 (no intermediate case). Here, two countries were equal in size and monetary policy shocks were assumed to follow two uncorrelated i.i.d. processes with same variances (for simplicity with $\sigma_u = \sigma_{u^*} = 1$). This parameter set-up arrived at inner solutions, so the share of LCP exporters always turned out to be between zero and one, and thus short-term pass-through of exchange rate was imperfect (between zero and one).

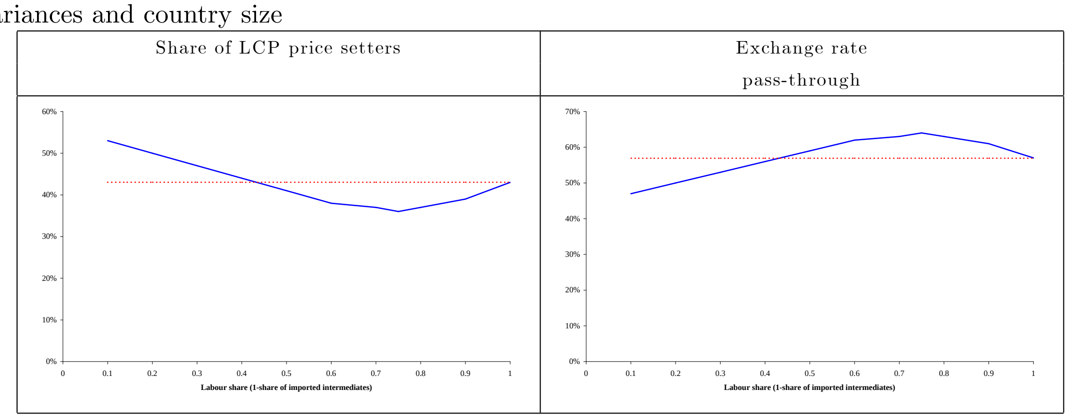
The numerical simulations of the model without intermediates resulted in approximately the same LCP shares as the analytically derived ones of Devereux et al (2004). According to the numerical simulations, the share of LCP exporters without intermediates is 43 per cent, so short-term exchange rate pass-through (to both export and import prices) was found to be slightly less than 60 per cent.

As *Figure 2.1* shows, the presence of imported intermediates does not significantly alter the results under symmetric and idiosyncratic monetary shocks. The equilibrium share of LCP price-setters changed by no more than 10 percentage points (in the extreme case with $\alpha = 0.1$). For more plausible values of α, e.g. between 0.5 and 1, the difference is even lower, no more than 6 percentage points.

The reason for the relatively stable LCP-shares is explained by exactly the fact that the two channels openness affect pass-through more or less offset each other when countries are identical and monetary policies are symmetrical. [32] This can also be partly due to the choice of production function (Leontieff technology) as in this case relative prices and hence relative consumption and production is only hardly affected by symmetric monetary shocks.

The first finding is that with symmetric monetary policies and identical countries the baseline endogenous pass-through model of Devereux et al (2004) is robust to the extent that production requires imported goods.

Figure 2.1 The effect of idiosyncratic monetary shocks with equal monetary variances and country size



2.4.2 Symmetric monetary policies and non-identical countries

As observed in the previous case, imported intermediates had two opposite effects, and these counteracted each other. Lower labour share increased the exposure of export revenues and the correlation of costs with the exchange rate. The two effects almost cancelled each other out. The next question is whether this may be due to the symmetric treatment of countries. In the next case I depart from identical countries and assume that Home country is smaller. One would suspect that now the two channels will no more offset each other. Now the assumption that firms behave similarly is no more feasible – the behaviour

[32] This is partly due the fact that imports are treated as fixed shares of production and their prices do not directly enter into firms' pricing problem.

of firms might be different in the small and in the bigger country. In the small Home country scenario Home country was assumed to be less than half of the Foreign economy ($n = 0.3$).

Figure 2.2 shows that indeed the two opposite effects do not fully offset each other. Compared with the case with equal country size, regardless of the share of imported intermediates, the share of LCP pricing among Home exporters is always somewhat lower, except when there is no role for imports in production. If $\alpha = 1$ LCP-price setters are almost the same in the small Home country scenario as in the identical countries scenario.

When allowing for imports in production, exporters in the small country are always less likely to price in the bigger country's currency. The explanation for this is that in this case, nominal exchange rate movements are more heavily influenced by what happens with the larger (Foreign) economy. Therefore, the first term in $\frac{var_{t-1}(s_t)}{2} - cov_{t-1}(s_t, mc_t)$ is less influenced by their choice than in the equal country case. However, the second term - the covariance term - is a decreasing function of α and thus, they will still more likely choose PCP policies when imports are used in production.

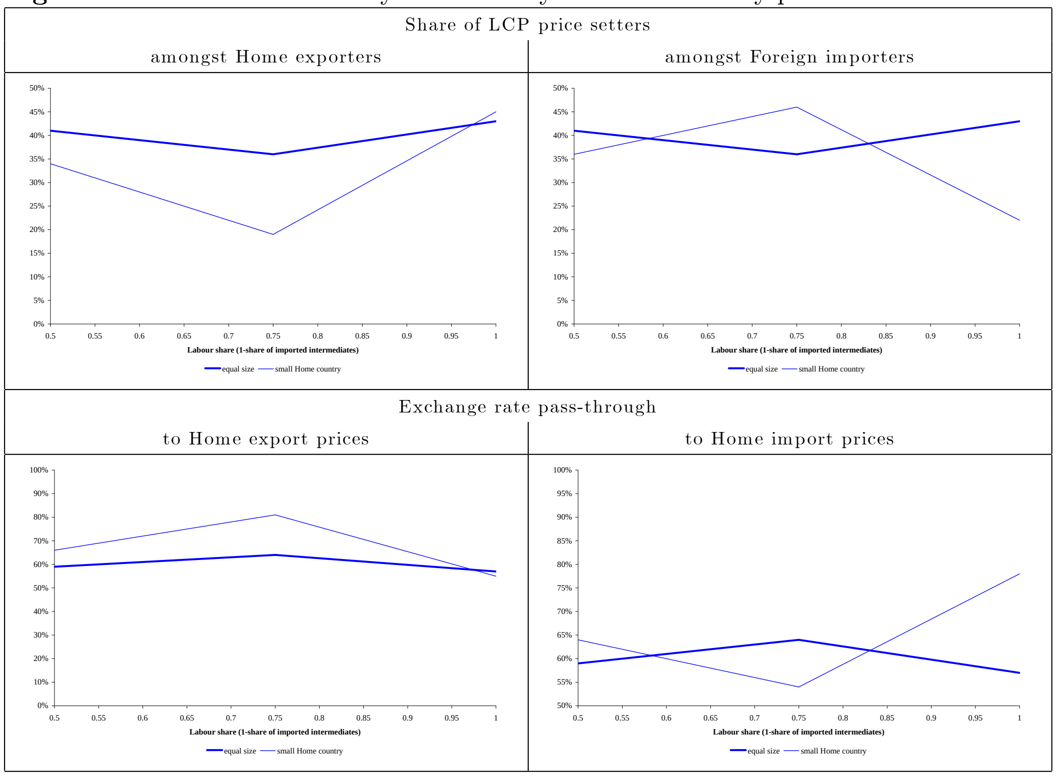
The model predicts that in smaller countries short-term pass-through to export prices in foreign currency is higher. This result can pose some critisism as it seems to be counter-intuitive. According to Dornbusch (1987) exchange rate pass-through may be higher if there are more exporters in comparison to the presence of local competitors. Hence, exchange rate pass-through might be inversely related to the country size.

On the other hand, some empirical evidence (see e.g. Campa and Goldberg (2002)) has found that country size is insignificant in the ranking of long-run exchange pass-through across countries.[33] So, one may not decide whether the model's prediction on the lower export price pass-through in a smaller country is realistic or not. All in all, this feature may point to a caveat of the model.

In most of the cases, expect for $\alpha = 0.75$, it is less likely that Foreign importers will opt for LCP pricing. Hence, short-term pass-through to Home import prices (in Home currency) is, in most cases, slightly higher when the Home economy is smaller in size.

[33] Interestingly, Frenkel et al (2005) found that developing countries in the 90's experienced a downward trend in pass-through, more so than did high-income countries. Therefore, slow and incomplete pass-through is no longer the feature of industrial economies. Hence, country size and pass-through might not necessarily be closely related.

Figure 2.2 The effect of country size under symmetric monetary policies



To sum up, under symmetric monetary policies, when the two countries' monetary authorities perform policies resulting in similar monetary stability, inserting imported intermediates does not change pass-through significantly. This is due to the dual role of imported goods: higher openness increases the exposure of revenues to exchange rate movements, and at the same time they also magnify the correlation between exchange rates and costs. The two effects more or less cancel each other out.

Country size matters somewhat when imported goods are used in production. It was found that in relatively small countries export price pass-through (in foreign currency) is higher. With regards to import price pass-through, in most cases it was found to be usually higher, but here it is the share of imported intermediates in production what matters.

2.4.3 Asymmetric monetary policies and identical countries

Previously it was shown that the presence of imported intermediates only slightly alter the conclusions of the endogenous pass-through model, with only labour being a factor of production. However, this is only the case when monetary shocks are symmetric.

According to Devereux et al (2004), there is a *'beggar-thy-neighbour'* effect of changes in the orientation of monetary policy. When Home country pursues more stable monetary policy than the Foreign country's central bank, more importers of the Foreign country would opt for pricing in the Home currency, and Home exporters would be more likely to choose PCP pricing policies. All agents will more probably price in the currency with the more stable monetary policy. In this sense, a country can stabilise inflation in two ways. First, it might run a relatively stable monetary policy, which alone contributes to more stable domestic inflation. Secondly, the endogeneity of pass-through serves as an *'automatic stabiliser'*, so that import price pass-through will decline.

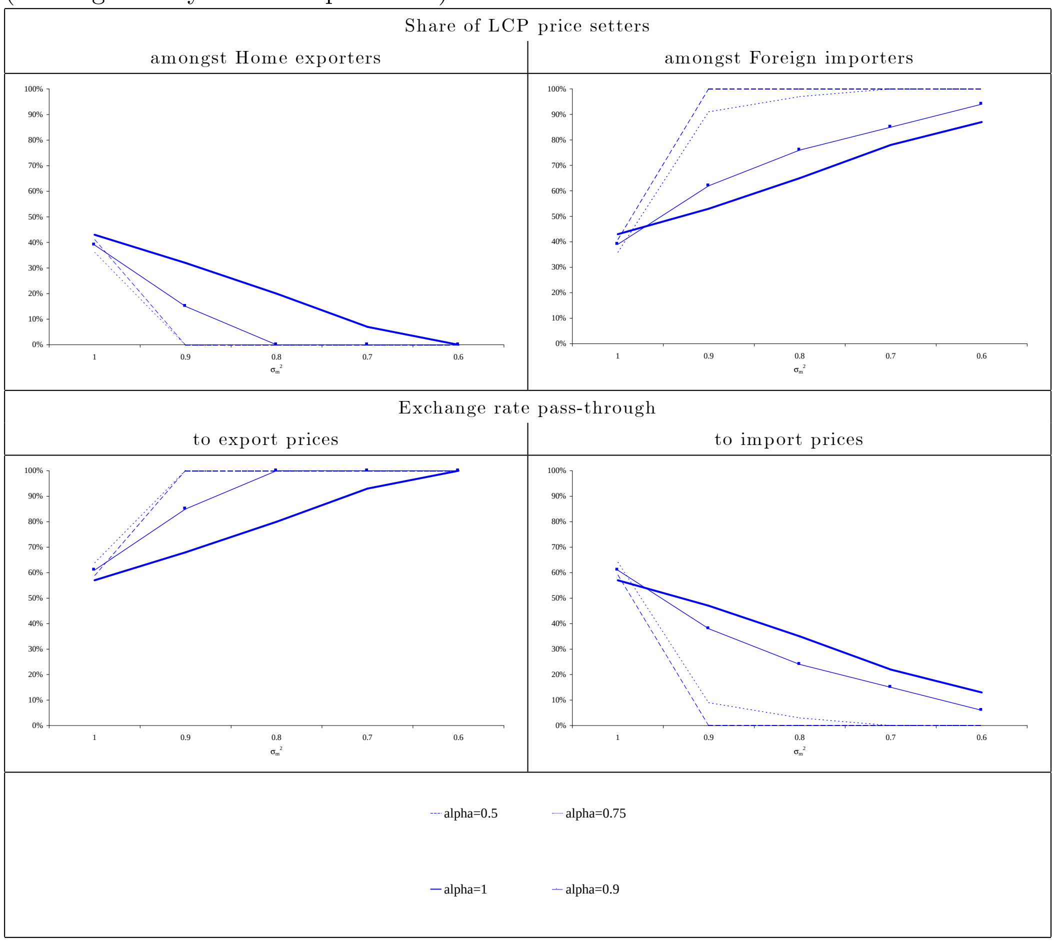
Lower pass-through then also moderates the effects of Foreign monetary policy shocks transmitted through nominal exchange rate fluctuations. What matters here is not the absolute but the relative variance of Home monetary policy shocks. The second channel, namely, the endogenous change in pass-through, only works when Home monetary authority creates relative monetary stability. A country can gain an extra stabilisation of inflation only if it maintains relative monetary stability. Pass-through is unaffected by a parallel reduction in monetary stability in both countries. A decline in pass-through in an economy as a result of stable monetary policy is analogous to a rise in pass-through in its partner economies.

For analysing how the reduction in Home monetary variance affects pass-through, I again numerically simulated the model under different scenarios for labour share and Home monetary variance, while Foreign monetary variance was held fixed at one. The numerically simulated model without imported intermediates replicated the analytical solutions of Devereux et al (2004).[34] The 'beggar-thy-neighbour' effect is shown by the thick lines on *Figure 2.3*. When monetary variance is reduced by 30 per cent, equilibrium pass-through to import prices declines by more than 30 percentage points and the pass-through to export prices becomes almost perfect. Most of Home exporters fix their prices in Home currency, and Foreign importers price in the Home currency.

As shown before, inserting imported intermediates in the model has only a minor effect on equilibrium when monetary policies were symmetric and equally stable. However, this no longer holds for asymmetric monetary policies. According to the simulations, the presence of these types of goods exaggerates the *'beggar-thy-neighbour'* effect. The two effects of imported intermediates do not fully cancel each other out. Nominal exchange rate variance decreases somewhat, but this effect remains limited. On the other hand, the reduction in Home monetary variance increases the covariance of nominal exchange rate and costs. This effect overcompensates for the fall in nominal exchange rate variance. This can be explained by their direct impact on cost and their indirect impact on the nominal exchange rate. In turn, introducing imported intermediates magnifies the *'beggar-thy-neighbour'* effect. This is robust across different scenarios for labour share.

[34] The numerical simulation of the model again slightly differed from that of the analytically derived one. This difference, however, is only modest.

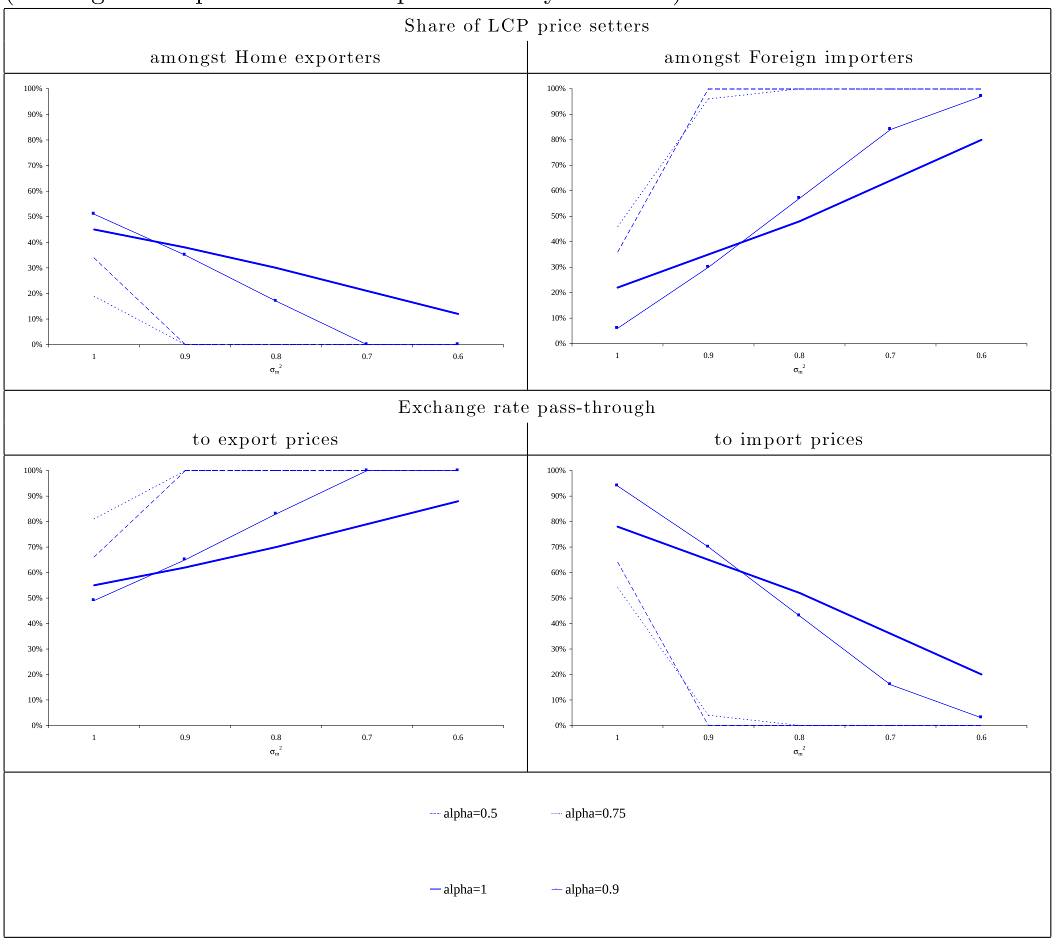
Figure 2.3 The effects of the fall in monetary variance with equal countries (starting from symmetric equilibrium)



2.4.4 Asymmetric monetary policies and non-identical countries

The exaggerating role of inserting imported intermediates on the *'beggar-thy-neighbour'* effect is even more pronounced when Home country is relatively small. In this case the starting point is always a higher export price pass-through (lower share of Home exporters choosing LCP strategy), and usually Foreign firms importing to the smaller market will more likely opt to hold their prices fixed in their currency. Smaller Home monetary variance always leads to an even lower share of exporters choosing LCP. The same mechanism can be observed with Foreign importers – monetary stability in the small Home country necessarily inspires them to price in the more stable currency. Of course, there is a level-effect, they will most likely price with PCP and not with LCP than in the smaller country (see *Figure 2.4*).

Figure 2.4 The effects of the fall in monetary variance with small Home country
(starting from equilibrium with equal monetary variances)



One can conclude that the *'beggar-thy-neighbour'* effect of creating monetary stability is robust across very different model set-ups. Country size and the incorporation of imported intermediates do not change the view that paass-through to import prices should drop when monetary policy is stabilised, but the intensity is highly dependent on country size and on the share of imported intermediates in production.

2.5 Conclusions

Endogenous exchange rate pass-through has serious implications for the conduct of optimal monetary policy in open economies. According to Devereux et al (2004) if the choice of currency is endogenous by firms, then countries stabilising domestic monetary policy have the advantage that firms will be encouraged to price in their currencies, and pass-through will diminish. Consequently, monetary policy can allow putting a larger weight on stabilising domestic inflation, and exchange rate fluctuations might have a minor role if pass-through to import prices decreases. Hence, even in open economies monetary policies might be able to stabilise inflation by not paying too much attention to nominal exchange rate fluctuations. There is, however, a debate in the literature whether monetary policy should or should not focus on external prices in open economies. The question posed in this chapter is how the endogeneity of pass-through is modified if imports are taken into account as a factor of production.

In this Chapter a theoretical model based on Devereux et al (2004) is built. The original model was modified with imported intermediates. In this model firms' profits are less exposed to exchange rate shocks than without it. Firms are more willing to price in their market's currency. However, there is a second channel working in the opposite direction: a greater role of imported intermediates would lead to higher exposure of revenues to nominal exchange rate shocks. Numerical simulations show that the two channels almost cancel each other out if countries are symmetric in size and monetary policies are uncorrelated and evenly stable.

According to simulations imported intermediates might play some role when countries are not equal in size. When one country is significantly smaller than the other, then exporting firms are more dependent on foreign demand, and their revenues are more exposed to nominal exchange rate fluctuations. Allowing for endogenous pass-through, the model suggests that in small countries, and when imports are used as factor of production, exchange rate pass-through to export prices will always be higher than in the benchmark case with identical countries. With regards to import price pass-through, the share of imported intermediates decides whether pass-through is higher or lower in the smaller country. In most of the cases analysed, import price pass-through in the smaller country turned out to be higher. These results seem to be against intuition and the argument of Dornbush (1987). However, the connection between country size and pass-through may be regarded to be empirically ambigous as noted by Campa and Goldberg (2006) and Barhoumi (2006).

The robust finding is that inserting imports into the production does not qualitatively alter the conclusion that if Home monetary policy becomes more stable, pass-through to import prices will drop. It is no longer the case, however, that imported intermediates have a minor effect on pass-through. The use of imported goods in production amplifies the gain in conducting stable monetary policies. A smaller drop in Home monetary variance results in the same drop in import price pass-through when imported goods are used. Hence, the argument for following stable monetary policies to stabilise prices is even more important when imports also serve as input for production. Incorporating imported intermediates also magnifies the gain of performing relatively stable monetary policy at Home when the Home country is relatively small in size.

One can thus conclude that the argument in favour of stabilising domestic inflation in open economies still holds. However, relative country size matters a lot and imported intermediates put even more emphasis on this argument.

Monetary policy should thus also focus on stabilising the costs of firms, in order to avoid massive cost shocks resulting from nominal exchange rate variability. Stable monetary policies always induce a shift in the currency of pricing and a drop in short-term pass-through. When monetary policy also takes into account import costs, monetary stability becomes even more necessary to stabilise inflation.

Chapter 3

3 An Estimated DSGE Model of the Hungarian Economy

3.1 Introduction

This chapter presents an estimated two-sector dynamic stochastic general equilibrium (DSGE) small-open-economy model first estimated on the Hungarian economy.[35] The basic setup of the model follows the tradition of Christiano et al. (2005) and Smets and Wouters (SW 2003), it features different types of frictions, real and nominal rigidities necessary to replicate the empirical persistence of Hungarian data. The model incorporates external habit formation in consumption, Calvo-type price and wage rigidity complemented with indexation to past prices and wages, adjustment costs of investments, adjustment cost of capacity utilization, and fixed cost in production. The model also contains liquidity-constrained rule-of-thumb consumers introduced by Galí et al. (2007). The approach of McCallum and Nelson (2007) which considers imports as production input is also utilized in this model.

There are several departure points from the *'standard'* DSGE tradition outlined above. First and foremost, apart from the well-known indexation setup, an additional inflation inertia is generated by learning. Rule-of-thumb price setters increase their prices by the *'perceived underlying'* rate of inflation, as in Yun (1996), and to some extent by the difference between the past actual and *'perceived underlying'* inflation rates, similarly to Christiano et al. (2001) and Smets and Wouters (2003). Rule-of-thumb agents' perception is formulated by a real time adaptive learning mechanism. This mechanism serves as an endogenous filtering of inflation. Inflation is separated into two endogenous components: filtered inflation (the *'perceived underlying inflation')*, and a cyclical inflation term. It is shown, that one can derive a New Keynesian Phillips Curve for the cyclical inflation which contains the same explanatory variables as in standard DSGE models. The learning rule governs the *'perceived underlying inflation'* component.[36]

Agents' perception on *'underlying'* inflation also affects longer term inflation movements. In contrast to standard DSGE models, this approach creates an additional inflation inertia. For example, when estimating the model on a disinflation period, agents only gradually learn the low inflation environment. Thus, there is no need to introduce an additional *'inflation target'* shock (as in Smets and Wouters (2003) or Adolfson et al (2006)) into the model to explain inflation dynamics during the disinflation.

This is demonstrated by an alternative model which is estimated with an additional *'inflation target'* shock mentioned above. According to the forecast

[35] This chapter is based on my joint paper with Balázs Világi (see Jakab and Világi (2008)).

[36] *'Underlying inflation'* is not core inflation, though both are less volatile than actual inflation.

error variance decomposition of the alternative model this shock would explain the bulk of the variance of short and long term inflation in Hungary. In other words, the model without the adaptive learning mechanism is not able to explain inflation dynamics in a country with ongoing disinflation. I argue that learning cannot be disregarded in DSGE models estimated on relatively high and persistent inflation.

A second departure point from the standard DSGE literature lies in the treatment of how monetary and exchange rate policy is handled. There were two different monetary regimes in Hungary over the estimation sample: between 1995 and 2001 a crawling-peg regime, and since 2001 an inflation-targeting regime. This structural break is explicitly taken into account in the estimation procedure and two slightly different models for the two subperiods are formulated. Exchange rate regime and the weight monetary policy devotes to inflation stabilization may have also consequences on the coefficients of Phillips curves, as well. Once there are significant breaks in monetary regimes, the econometrician should take this into account seriously. Hungary also serves as a nice example where the conduct of monetary policy changed markedly. I also show how the regime change affected the coefficients of the Phillips curves.

Though not unique in the literature, the model is multi-sectoral. There are two sectors producing domestic and exported final goods. This is key in explaining a small, open economy like Hungary, where the export sector shows very different productivity and price developments than the domestic one. An additional real rigidity is also introduced: adjustment cost on the boundle consisting of labor and import, this is a key determinant in slowing down the model's real responses to shocks.

As now becomes standard, the model is estimated by Bayesian method described in An and Schorfheide (2005). The method based on maximization of the likelihood function, derived from the rational-expectations solution by the Kalman-filter, combined with prior distributions. To characterize the posterior density function of the estimated parameters the random-walk Metropolis-Hastings (MH) algorithm is applied.

The main results are the following. The estimated values of the Calvo parameters for consumer price setting are close to the ones usually estimated for euro-zone. On the other hand, the Calvo coefficients for wage setting are generally estimated lower than euro-area estimates. Unlike Calvo coefficients, the monetary regime shift is mostly felt in the indexation of consumer prices as it is estimated to be significantly lower in the inflation targeting regime.In contrast, wage indexation parameters are estimated to be stable across the two regimes and generally lower than in the eurozone. Adjustment cost of investment is found to be high compared to other DSGE models.

The estimated value of the interest-rate smoothing parameter is significantly lower than various euro-area and US estimates. It is important to note that this result is not driven by the choice of the accompanying prior distribution. A relatively uninformative Uniform prior is imposed on this parameter.

Estimated impulse-response functions replicate qualitatively the behavior of other New Keynesian models quite well. The main difference is that investments react much less to most shocks than it is common in similar models. The model features a hump-shaped effect on both output and inflation to a monetary tightening. A positive productivity shock results in increasing output and production, but decreasing inflation and employment as documented in Galí (2007). The response of cyclical inflation and wages are less persistent than those adjusted for agents' perception on *underlying* inflation (the response of original price and wage inflation).

The crowding-out effect of a government-consumption shock is also observable, however, due to the presence of rule-of-thumb consumers the estimated model is able to replicate the co-movement of government and private consumption. It is important to note, that in general short term reactions are highly affected by the presence of non-optimizing consumers. The relatively high adjustment cost of investment implies a generally smoother reaction of investments to shocks.

Variance decomposition reveals that both cyclical and permanent (*'perceived underlying'*) component of inflation can be explained by productivity, investment, consumer preference and markup shocks. That is, the endogenous learning process in this DSGE model was able to capture longer term inflation movements without introducing an additional exogenous shock.

To show this, an alternative model without endogenous real time adaptive learning of *'underlying inflation'* is also estimated. I conclude that the inclusion of adaptive learning is not really responsible for creating an *'intrinsic'* inertia in inflation. However, according to variance decomposition long-term movements of inflation are mostly captured by the shock to '*underlying'* inflation'. This reveals that the approach of the baseline model was necessary to explain long term disinflation in Hungary.

In the long run real variables are heavily influenced by both the external demand and the productivity shock. These shocks are the prime source of output fluctuation in a small, open economy like Hungary. Real effect of the financial premium and the monetary-policy shock is found negligible, which is in sharp contrast with the finding of Smets and Wouters (2003). This finding is, however, in accordance with Vonnák (2007) and Jakab et al (2006) that monetary policy has a rather limited effect on output in Hungary.

This model may serve as a basis for policy simulations at the central bank of Hungary (Magyar Nemzeti Bank). Natural directions would be the refinement of labor market (by inserting search and marching frictions as in Jakab and Kónya (2008)) or the research on optimal monetary policy rules in a more detailed manner.

The chapter is structured as follows. *Section 3.2* presents the estimated DSGE model. *Section 3.3* describes the data set and the applied estimation method, and presents estimation results. In *Section 3.4* the evolution of shocks is described. In *Section 3.5* and *3.6* impulse responses and forecast error variance decomposition of the model are analysed. In *Section 3.7* an alternative model without adaptive learning of *'underlying inflation'* is presented. *Section 3.8* provides conclusions.

3.2 The model

3.2.1 Production

Production has a hierarchical structure: at the first stage labor and imported inputs are transformed into an intermediate input in a perfectly competitive industry. At the second stage the intermediate input and capital are used to produce differentiated goods in a monopolistically competitive industry. Finally, a homogenous final good is produced by the differentiated goods in a perfectly competitive environment. There two sectors in the economy: a domestic production sector and exports sector, labeled by d and x, respectively.

Final good y_t^s in sector s $(s = d, x)$ is produced in a competitive market by a constant-returns-to-scale technology from a continuum of differentiated intermediate goods $y_t^s(i)$, $i \in [0, 1]$. The technology is represented by the following CES production function:

$$y_t^s = \left(\int_0^1 y_t(i)^{\frac{\theta-1}{\theta}} \, di \right)^{\frac{\theta}{\theta-1}}, \tag{113}$$

where $\theta > 1$ measures the degree of the elasticity of substitution. As a consequence, the price index P_t^s is given by

$$P_t^s = \left(\int_0^1 P_t^s(i)^{1-\theta} \, di \right)^{\frac{1}{1-\theta}}, \tag{114}$$

where $P_t^s(i)$ denotes the prices of differentiated goods $y_t^s(i)$, and the demand for $y_t^s(i)$ is determined by

$$y_t^s(i) = \left(\frac{P_t^s}{P_t^s(i)} \right)^{\theta} y_t^s. \tag{115}$$

Cost minimization

The continuum of goods $y_t^s(i)$ are produced in a monopolistically competitive market. Each $y_t^s(i)$ is made by an individual firm, and they apply the same CES technology. Firm i uses technology

$$y_t^s(i) = A_t \left(\bar{\alpha}_s^{\frac{1}{\varrho}} \bar{k}_t^s(i)^{\frac{\varrho-1}{\varrho}} + (1 - \bar{\alpha}_s)^{\frac{1}{\varrho}} z_t^s(i)^{\frac{\varrho-1}{\varrho}} \right)^{\frac{\varrho}{\varrho-1}} - \bar{f}_s, \tag{116}$$

where $\bar{k}_t^s(i)$ is the firm's effective utilization of physical capital, $\bar{k}_t^s(i) = u_t k_t^s(i)$, where u_t is the degree of capital utilization explained in detail in the next section, $k_t^s(i)$ the firm's utilization of the homogenous capital good. $z_t^s(i)$ is the firm's utilization of a composite intermediate input good z_t^s. Variable A_t is a uniform exogenous productivity factor and $\bar{f}_s$ is uniform real fixed cost of the industry. The parameter $0 < \varrho$ measures the elasticity of substitution between $\bar{k}_t^s$ and z_t^s and $0 < \bar{\alpha}_s < 1$. Good $z_t^s(i)$ is composed by composite labor and imported inputs, Solution of firms' cost minimization problem implies that their marginal cost is

$$MC_t^s = A_t^{-1} \left[\bar{\alpha}_s \left(R_t^k \right)^{1-\varrho} + (1-\bar{\alpha}_s) \left(W_t^{zs} \right)^{1-\varrho} \right]^{\frac{1}{1-\varrho}}, \tag{117}$$

where R_t^k is the rental rate of capital and W_t^{zs} is the price of z_t^s. Solution of cost minimization also provides demand for inputs, represented by

$$\begin{aligned} \bar{k}_t^s(i) &= \bar{\alpha}_s \left(\frac{mc_t^s}{r_t^k} \right)^{\varrho} \frac{y_t^s(i) + \bar{f}_s}{A_t^{1-\varrho}}, \\ z_t^s(i) &= (1-\bar{\alpha}_s) \left(\frac{mc_t^s}{w_t^z} \right)^{\varrho} \frac{y_t^s(i) + \bar{f}_s}{A_t^{1-\varrho}}, \end{aligned}$$

where $mc_t^s = MC_t^s / P_t$. Let us define the following sectoral aggregate variables.

$$k_t^s = \int_0^1 k_t^s(i)\, di, \qquad z_t^s = \int_0^1 z_t^s(i)\, di.$$

Aggregating individual demand functions and using equation (115) results in

$$u_t k_t^s = \bar{\alpha}_s \left(\frac{mc_t^s}{r_t^k} \right)^{\varrho} \frac{y_t^s DP_t^s + \bar{f}_s}{A_t^{1-\varrho}}, \tag{118}$$

$$z_t^s = (1-\bar{\alpha}_s) \left(\frac{mc_t^s}{w_t^z} \right)^{\varrho} \frac{y_t^s DP_t^s + \bar{f}_s}{A_t^{1-\varrho}}, \tag{119}$$

where variable DP_t^s represents price dispersion,

$$DP_t^s = \int_0^1 \left(\frac{P_t}{P_t(i)} \right)^{\theta} di.$$

The composite intermediate input is produced in a competitive industry by the following CES technology,

$$z_t^s = \left(\bar{a}_s^{\frac{1}{\varrho_z}} \left(m_t^s \right)^{\frac{\varrho_z - 1}{\varrho_z}} + (1-\bar{a}_s)^{\frac{1}{\varrho_z}} \left(l_t^s \right)^{\frac{\varrho_z - 1}{\varrho_z}} \right)^{\frac{\varrho_z}{\varrho_z - 1}} - z_t^s \Phi_z \left(z_t^s \right). \tag{120}$$

where l_t^s is labor and m_t^s is the imported input good m_t^s. Furthermore $0 < \varrho_z$ and $0 < \bar{a}_s < 1$, and the adjustment cost function

$$\Phi_{zs} \left(z_t^s \right) = \frac{\phi_z}{2\bar{z}^s} \left(\frac{z_t^s}{\bar{z}^s} - 1 \right)^2, \qquad \phi_z > 0.$$

Properties of this function are $\Phi'_{zs} > 0$, $\Phi_{zs}\left(\bar{z}^s\right) = \Phi'_{zs}\left(\bar{z}^s\right) = 0$. $\bar{z}^s$ is the steady state level of the composite input. The price of composite input W_t^{zs} is equal to the marginal cost of its production. In *Appendix B.1.1* it is shown that marginal cost is given by,

$$W_t^{zs} = \left[\bar{a}_s W_t^{1-\varrho_z} + (1-\bar{a}_s) \left(e_t P_t^{m*} \right)^{1-\varrho_z} \right]^{\frac{1}{1-\varrho_z}} \left[1 + \Phi_{zs}\left(z_t^s \right) + z_t^s \Phi'_{zs}\left(z_t^s \right) \right], \tag{121}$$

where W_t is the nominal wage, P_t^{m*} is the foreign-currency price of imported inputs and e_t is the nominal exchange rate. Furthermore, demand for production inputs are given by the following equations,

$$l_t^s = \bar{a}_s \left(\frac{\bar{w}_t^{zs}}{w_t} \right)^{\varrho_z} z_t^s \left[1 + \Phi_{zs} \left(z_t^s \right) \right], \tag{122}$$

$$m_t^s = (1 - \bar{a}_s) \left(\frac{\bar{w}_t^{zs}}{q_t P_t^{m*}} \right)^{\varrho_z} z_t^s \left[1 + \Phi_{zs} \left(z_t^s \right) \right], \tag{123}$$

where

$$\bar{w}_t^{zs} = \left[\bar{a}_s w_t^{1-\varrho_z} + (1 - \bar{a}_s) \left(q_t P_t^{m*} \right)^{1-\varrho_z} \right]^{\frac{1}{1-\varrho_z}},$$

and $w_t = W_t / P_t$ is the real wage, $q_t = e_t / P_t$ is the domestic component of the real exchange rate.

Price setting

Let us consider how firms in the domestic production sector set their prices. To simplify notation I drop index d of the sectoral price index. It is assumed that prices are sticky: as in the model of Calvo (1983), each intermediate good producer at a given date changes its price in a rational, optimizing, forward-looking way with a constant probability of $1 - \gamma_d$. Those firms which do not optimize at the given date follow a rule of thumb. Rule of thumb price setters increase their prices by the expected average rate of inflation, as in Yun (1996), and to some extent by the difference between the past actual and *'perceived underlying'* inflation rates, similarly to Christiano et al. (2001) and Smets and Wouters (2003). Formally, if firm i does not optimize at date:

$$P_t(i) = P_{t-1}(i) \Pi_{t-1}^I = P_{t-1}(i) \left(\frac{\Pi_{t-1}}{\bar{\Pi}_{t-1}} \right)^{\vartheta_d} \bar{\Pi}_t$$

where $\Pi_{t-1} = P_{t-1}/P_{t-2}$, $\bar{\Pi}_t$ is the *'perceived underlying'* inflation. ϑ_d measures the degree of indexation according to past inflation. The above formula implies if a given firm does not optimize between $t+1$ and T its price at date T is given by

$$P_T(i) = P_t(i) \Pi_{T,t}^I = P_t(i) \Pi_T^I \Pi_{T-1}^I \cdots \Pi_t^I. \tag{124}$$

If $P_t(i)$ is the chosen price of a firm at date t, then its profit at T will be

$$\begin{aligned} V_T(P_t(i)) &= y_T^d(i) \left(\tau_t^d P_T(i) - MC_T^d \right) - \bar{f}_d. \\ &= y_T^d P_T^\theta \left[\left(P_t(i) \Pi_{T,t}^I \right)^{1-\theta} - \left(P_t(i) \Pi_{T,t}^I \right)^{-\theta} MC_T^d \right] - \bar{f}_d, \end{aligned}$$

where the second equation is a consequence of formulas (115) and (124). If firm i sets its price optimally at date t it solves the following maximization problem.

$$\max_{P_t(i)} = \mathrm{E}_t \left[\sum_{T=t}^{\infty} (\gamma_d)^{T-t} D_{T,t} V_T(P_t(i)) \right],$$

where $D_{T,t}$ is the stochastic discount factor,

$$D_{T,t} = \beta^{T-t} \frac{\Lambda_T^o / P_T}{\Lambda_t^o / P_t},$$

and Λ_t^o is the marginal utility of consumption of optimizing consumers who own the firms. It is explained in detail in the next section.

The first order condition is

$$\sum_{T=t}^{\infty} \gamma_d^{T-t} \mathrm{E}_t \left[D_{T,t} y_t^d \left(\frac{P_T}{P_t(i) \Pi_{T,t}^I} \right)^{\theta} \left(\tau_T^d \Pi_{T,t}^I - \frac{\theta}{\theta - 1} \frac{P_T mc_T^d}{P_t(i)} \right) \right] = 0,$$

where $mc_t^d = MC_T^d / P_T$ is the real marginal cost. Rearranging it yields

$$\begin{aligned} \frac{P_t(i)}{P_t} \sum_{T=t}^{\infty} (\gamma_d \beta)^{T-t} \mathrm{E}_t \left[\Lambda_T^o y_t^d \tau_t^d \left(\frac{P_T}{P_t \Pi_{T,t}^I} \right)^{\theta - 1} \right] = \\ \frac{\theta}{\theta - 1} \sum_{T=t}^{\infty} (\gamma_d \beta)^{T-t} \mathrm{E}_t \left[\Lambda_T^o y_t^d \left(\frac{P_T}{P_t \Pi_{T,t}^I} \right)^{\theta} mc_T^d \right]. \end{aligned} \tag{125}$$

Equation (125) implies that all firms choose the same $P_t(i)$. Let us denote this uniform price by $P_t^\star$. Define $\mathcal{P}_t = P_t^\star / P_t$. In *Appendix B.1.2* it is shown that condition (125) can be expressed in a recursive form,

$$\mathcal{P}_t = \frac{\theta}{\theta - 1} \frac{\mathcal{Z}_t^1}{\mathcal{Z}_t^2}, \tag{126}$$

where

$$\mathcal{Z}_t^1 = \Lambda_t^o y_t^d mc_t^d + \beta \gamma_d \mathrm{E}_t \left[\left(\frac{\Pi_{t+1}}{\Pi_t^I} \right)^{\theta} \mathcal{Z}_{t+1}^1 \right], \tag{127}$$

$$\mathcal{Z}_t^2 = \tau_t^d \Lambda_t^o y_t^d + \beta \gamma_d \mathrm{E}_t \left[\left(\frac{\Pi_{t+1}}{\Pi_t^I} \right)^{\theta - 1} \mathcal{Z}_{t+1}^2 \right]. \tag{128}$$

Equation (113) and the price-setting assumptions imply that the evolution aggregate price index is given by

$$P_t^{1-\theta} = (1 - \gamma_d) \left(P_t^\star \right)^{1-\theta} + \gamma_d \left(P_{t-1} \Pi_{t-1}^I \right)^{1-\theta},$$

rearranging it yields

$$\mathcal{P}_t^{1-\theta} = \frac{1 - \gamma_d \left(\frac{\Pi_t}{\Pi_{t-1}^I} \right)^{\theta - 1}}{1 - \gamma_d}. \tag{129}$$

In export sector price setting is similar to that of domestic production sector, however prices are set in foreign currency That is, firms set $P_t^{x*} = P_t^x / e_t$, where e_t is the nominal exchange rate.

The price indexation scheme of the sector is

$$P_T^{x*}(i) = P_t^{x*}(i)\Pi_{T,t}^{I} = P_t(i)\Pi_T^{Ix}\Pi_{T-1}^{Ix}\cdots\Pi_t^{Ix},$$

where

$$\Pi_t^{Ix} = \left(\frac{\Pi_t^{x*}}{\bar{\Pi}_t^{x*}}\right)^{\vartheta_x}\bar{\Pi}_{t+1}^{x*}$$

and $\Pi_t^{x*} = P_t^{x*}/P_{t-1}^{x*}$, $\bar{\Pi}_t^{x*}$ is the *'underlying'* export price inflation, ϑ_x represents the degree of indexation according to past export price inflation.

If $P_t^{x*}(i)$ is the chosen price of a firm at date t, then its profit will be at date T

$$\begin{aligned}
V_T^x(P_t^{x*}(i)) &= y_T^d(i)\left(\tau_t^x e_T P_T^{x*}(i) - MC_T^x\right) - \bar{f}_x. \\
&= y_T^x P_T^\theta\left[\left(e_T P_t^{x*}(i)\Pi_{T,t}^{Ix}\right)^{1-\theta} - \left(e_T P_t^{x*}(i)\Pi_{T,t}^{Ix}\right)^{-\theta} MC_T^x\right] - \bar{f}_x.
\end{aligned}$$

The maximization problem of firm i is

$$\max_{P_t^{x*}(i)} = \mathrm{E}_t\left[\sum_{T=t}^{\infty}(\gamma_x)^{T-t}D_{T,t}V_T^x(P_t^{x*}(i))\right].$$

The first order condition is

$$\sum_{T=t}^{\infty}\gamma_x^{T-t}\mathrm{E}_t\left[D_{T,t}y_t^x\left(\frac{P_T^{x*}}{P_t^{x*}(i)\Pi_{T,t}^{Ix}}\right)^{\theta}\left(\tau_T^x\Pi_{T,t}^{I*} - \frac{\theta}{\theta-1}\frac{e_T P_T^{x*}mc_T^{x*}}{P_t^{x*}(i)}\right)\right] = 0,$$

where

$$mc_t^{x*} = \frac{MC_T^x}{e_T P_T^{x*}} = \frac{P_T mc_T^x}{e_T P_T^{x*}}. \tag{130}$$

As in the previous case, all firms choose the same $P_t^{x*}(i)/P_t^{x*}$. Its common value is denoted by $\mathcal{P}_t^x$. In *Appendix B.1.2* it is shown that the above first-order condition can be expressed recursively as,

$$\mathcal{P}_t^x = \frac{\theta}{\theta-1}\frac{\mathcal{Z}_t^{x1}}{\mathcal{Z}_t^{x2}}, \tag{131}$$

where

$$\mathcal{Z}_t^{x1} = \frac{P_t^{x*}}{q_t}\Lambda_t^o y_t^x mc_t^{x*} + \beta\gamma_x\mathrm{E}_t\left[\left(\frac{\Pi_{t+1}^{x*}}{\Pi_t^{Ix}}\right)^{\theta}\mathcal{Z}_{t+1}^{x1}\right], \tag{132}$$

$$\mathcal{Z}_t^{x2} = \tau_t^x\frac{P_t^{x*}}{q_t}\Lambda_t^o y_t^x + \beta\gamma_x\mathrm{E}_t\left[\left(\frac{\Pi_{t+1}^{x*}}{\Pi_t^{Ix}}\right)^{\theta-1}\mathcal{Z}_{t+1}^{x2}\right]. \tag{133}$$

As above, it is possible to show that

$$(\mathcal{P}_t^x)^{1-\theta} = \frac{1-\gamma_x\left(\frac{\Pi_t^{x*}}{\Pi_{t-1}^{Ix}}\right)^{\theta-1}}{1-\gamma_x}. \tag{134}$$

3.2.2 Households

Optimizing households

The domestic economy is populated by a continuum of infinitely-lived households. Fraction $\bar{\omega}^o$ of households choose their consumption stream in the standard rational optimizing manner. These optimizing households have labor and capital income and they own domestic firms. The expected utility function of optimizing household j is

$$\sum_{t=0}^{\infty} \beta^t \mathrm{E}_0 \left[\eta_t^c \left\{ u(H_t^o(j)) - \eta_t^l v(l_t(j)) \right\} \right], \tag{135}$$

for all $j \in [0,1]$. $H_t^o(j) = c_t^o(j) - hc_{t-1}^o$, where $c_t^o(j)$ denotes the consumption of household j at date t, c_{t-1}^o is the aggregate consumption of optimizers at date $t-1$, parameter $h \in [0,1]$ measures the strength of external habit formation, $l_t(j)$ is the labor supply of household j, η_t^c and η_t^l are preference shocks. Furthermore, $u(H) = H^{1-\sigma}/(1-\sigma)$, and $v(l) = l^{1+\varphi}/(1+\varphi)$, σ, $\varphi > 0$.

The intertemporal budget constraint of a given household can be written in the form

$$\begin{aligned} & P_t c_t^o(j) + P_t I_t(j) + \frac{B_t(j)}{1+i_t} = \\ & B_{t-1}(j) + X_t^w(j) + W_t(j) l_t(j) + P_t r_t^k u_t(j) k_t(j) - \Psi(u_t(j)) P_t k_t(j) + Div_t - T_t^o, \end{aligned} \tag{136}$$

where P_t is the consumer price index, $B_t(j)$ is the household's holding of riskless nominal bonds at the beginning of time t, i_t is the corresponding one-period nominal interest rate, Div_t denotes dividends derived form firms. It is assumed that dividends are equally distributed among firms. $k_t(j)$ is the stock of physical capital supplied by the household, $u_t(j)$ is the utilization rate of capital ($\bar{k}_t = u_t k_t$). T_t^o denotes the lump-sum tax levied on optimizing households. Ψ is the cost of the capital utilization rate, it is assumed that

$$\Psi\left(u_t\right) = r^k \psi \left[\exp\left(\frac{u_t - 1}{\psi} \right) - 1 \right].$$

This implies that at the steady state ($u = 1$) $\Psi(1) = 0$, Ψ'^k, and $\psi = \Psi'(1)/\Psi''(1)$. $I_t(j)$ denotes investments in physical capital. $W_t(j)$ is the nominal wage paid to household j. Households supply differentiated labor, hence the wage paid to individual households can be different. On the other hand, X_t^w is a state-contingent security which eliminates the risk of heterogeneous labor supply and labor income. Physical capital accumulation is described by

$$k_{t+1}(j) = (1-\delta) k_t(j) + \left[1 - \Phi_I \left(\frac{\eta_t^I I_t(j)}{I_{t-1}(j)} \right) \right] I_t(j), \tag{137}$$

where function Φ_I represents investments adjustment costs, and η_t^I is an exogenous shock. It is assumed that

$$\Phi_I \left(\frac{\eta_t^I I_t(j)}{I_{t-1}(j)} \right) = \frac{\phi_I}{2} \left(\frac{\eta_t^I I_t(j)}{I_{t-1}(j)} - 1 \right)^2, \qquad \phi_I > 0.$$

This implies that $\Phi'_I > 0$, and in the steady state $\Phi'_I(1) = \Phi'_I(1) = 0$.

An optimizing household chooses the trajectory of its consumption, bond-holding, investments, physical capital and capital utilization. It is assumed that a certain household supplying type j of labor belongs to a trade-union representing the interest of optimizing and non-optimizing households supplying type j of labor. The union determines the labor supply and the nominal wage of its members, all members accept its decision.

The formal optimization problem of the households is the following: they maximize the objective function (135) subject to the budget constraint (136), the investments equation (137), non-negativity constraints on consumption and investments, and no-Ponzi schemes. The characterization of the solution of the above optimization problem can be found in *Appendix B.1.3*.

Due to the existence of asset X_t^w the wage incomes of all households are the same. As a consequence, all households choose the same consumption allocation. I, therefore, drop index j from subsequent notations.

The path of consumption is determined by the following Euler equation.

$$\frac{\Lambda_t^o}{P_t} = \beta(1 + i_t)\mathrm{E}_t \left[\frac{\Lambda_{t+1}^o}{P_{t+1}}\right], \tag{138}$$

where Λ_t^o is the marginal utility of consumption,

$$\Lambda_t^o = \eta_t^c (c_t^o - h c_{t-1}^o)^{-\sigma}. \tag{139}$$

The trajectory of investments is described by equation

$$\begin{aligned} Q_t \left[1 - \Phi_I\left(\frac{\eta_t^I I_t}{I_{t-1}}\right) - \Phi'_I\left(\frac{\eta_t^I I_t}{I_{t-1}}\right)\frac{\eta_t^I I_t}{I_{t-1}}\right] = \\ 1 - \beta \mathrm{E}_t \left[D_{t+1,1} Q_{t+1} \Phi'_I\left(\frac{\eta_{t+1}^I I_{t+1}}{I_t}\right)\frac{\eta_{t+1}^I I_{t+1}^2}{I_t^2}\right], \end{aligned} \tag{140}$$

where Q_t is the shadow price of capital. The portfolio choice between bond and physical capital is given by

$$Q_t = \mathrm{E}_t \left[D_{t+1,1}\left(Q_{t+1}(1-\delta) + u_{t+1} r_{t+1}^k - \Psi(u_{t+1})\right)\right]. \tag{141}$$

Finally, the following condition describes the choice of capital utilization.

$$r_t^k = \Psi'(u_t(j)). \tag{142}$$

Non-optimizing households

Fraction $\bar{\omega}^{no}$ of households are liquidity constrained.[37] Their consumption

[37] I inserted pensioners into the model because otherwise labor (hours) would behave too eratically. These types of agents do not supply labor and only consume their income, hence total economy labor supply will not change as much as without them. The second way of 'slowing down' employment adjustment was to introduce an auxiliary equation linking hours and employment. In Hungary reliable data are only available for employment. Thus, when estimating the model to data this additional equation and the presence of pensioners helped in matching the relatively low variation in employment.

follows a simple rule of thumb.

$$P_t c_t^{no}(j) = X_t^w(j) + W_t(j) l_t(j).$$

Due to the existence of asset X_t^w their wage income and consumption are uniform. As a consequence,

$$P_t c_t^{no} = W_t l_t. \tag{143}$$

Fraction $\bar{\omega}^p$ of households are pensioners. It is assumed that they also consume their total income adjusted by the *'Swiss indexation formula'*. That is, it is assumed that their consumption proportional to the average of price and wage level,

$$P_t c_t^p = c^p w^{-\frac{1}{2}} \left(W_t P_t\right)^{\frac{1}{2}}, \tag{144}$$

where c^p and w are the steady-state values of pensioners' consumption and real wages, respectively.

Wage setting

There is monopolistic competition in the labor market, different types of labor are supplied by households. Wages is set by which representing the interest of households active on the labor market, that is, that of optimizers and non-optimizers. Union j sets $W_t(j)$, the nominal wage level belonging to type j of labor. The composite labor good of the economy is a CES aggregate of different types of labor,

$$l_t = \left(\int_0^1 l_t(j)^{\frac{\theta_w - 1}{\theta_w}}\, dj\right)^{\frac{\theta^w}{\theta^w - 1}},$$

where $\theta^w > 1$ is elasticity of substitution between different types of labor. This implies that the demand for labor supplied by household j is given by

$$l_t(j) = \left(\frac{W_t}{W_t(j)}\right)^{\theta_w} l_t, \tag{145}$$

where the aggregate wage index W_t is defined by

$$W_t = \left(\int_0^1 W_t(j)^{1-\theta_w}\, dj\right)^{\frac{1}{1-\theta_w}}.$$

It is assumed that there is sticky wage setting in the model, as in the paper of Erceg et al. (2000). Similarly to Calvo (1983), every union at a given date changes its wage in a rational, optimizing forward-looking manner with probability $1-\gamma_w$. All those unions, which do not optimize at the given date follow a rule of thumb similar to that of producers. Using the notation introduced in the previous subsection, the price setting scheme of the non-optimizers is described by formula

$$W_T(i) = W_t(i)\Pi_{T,t}^{Iw} = P_t(i)\Pi_T^{Iw}\Pi_{T-1}^{Iw}\cdots\Pi_t^{Iw},$$

where

$$\Pi_t^{Iw} = \left(\frac{\Pi_t^w}{\bar{\Pi}_t}\right)^{\vartheta_w} \bar{\Pi}_{t+1}$$

and $\Pi_t^w = W_t/W_{t-1}$, ϑ_w represents the degree of indexation according to past inflation.

If a union chooses it wage optimally at date t it has to take into account that it will follow the rule of thumb at $t+1$ with a probability of γ_w, at $t+2$ with γ_w^2, and so on. Hence it has to weight the objective function with the above sequence of probabilities. That is, it maximizes formula

$$\sum_{t=T}^{\infty} (\gamma_w \beta)^{T-t} \mathrm{E}_t \left[\eta_t^c \left\{ \frac{\bar{\omega}^o U(H_T^o) + \bar{\omega}^{no} U(H_T^{no})}{\bar{\omega}^o + \bar{\omega}^{no}} - \eta_t^l V(l_T(j)) \right\} \right],$$

subject to the budget constraints (136) and (143), the labor demand equation (145) and the above indexation formula, where $H_t^{no} = c_t^{no} - hc_{t-1}^{no}$.

The first-order conditions of this problem with respect to the two types of consumption and the nominal wages are the following.

$$\lambda_T^o = (\gamma_w \beta)^{T-t} \frac{\Lambda_t^o}{P_T}, \qquad \lambda_T^{no} = (\gamma_w \beta)^{T-t} \frac{\Lambda_t^{no}}{P_T} \tag{146}$$

$$\sum_{T=t}^{\infty} (\gamma_w \beta)^{T-t} \mathrm{E}_t \left[l_T \left(\frac{W_T}{W_t(j) \Pi_{T,t}^{Iw}} \right)^{\theta_w} \lambda_T^l \tau_T^w \Pi_{T,t}^{Iw} \right] = \tag{147}$$

$$\frac{\theta_w}{\theta_w - 1} \sum_{T=t}^{\infty} (\gamma_w \beta)^{T-t} \mathrm{E}_t \left[l_T \left(\frac{W_T}{W_t(j) \Pi_{T,t}^{Iw}} \right)^{\theta_w} \eta_T^c \eta_T^l \frac{l_T(j)^{\varphi}}{W_t(j)} \right],$$

where λ_T^o and λ_T^{no} are state dependent Lagrange multipliers, $\Lambda_T^{no} = \eta_T^c \left(H_t^{no}\right)^{-\sigma}$ and $\lambda_T^l = \lambda_T^o + \lambda_T^{no}$. It is shown in *Appendix B.1.4* that the above first-order conditions imply that aggregate wage setting can be described by the following recursive form,

$$\mathcal{W}_t = \left(\frac{\theta^w}{\theta^w - 1} \frac{\mathcal{Z}_t^{w1}}{\mathcal{Z}_t^{w2}} \right)^{1+\theta_w \varphi}, \tag{148}$$

where

$$\mathcal{Z}_t^{w1} = \eta_t^c \eta_t^l l_t^{\varphi+1} + \beta \gamma_w \mathrm{E}_t \left[\left(\frac{\Pi_{t+1}^w}{\Pi_t^{Iw}} \right)^{\theta_t^w (1+\varphi) - 1} \mathcal{Z}_{t+1}^{w1} \right], \tag{149}$$

$$\mathcal{Z}_t^{w2} = \tau_t^w \Lambda_t^a w_t l_t + \beta \gamma_w \mathrm{E}_t \left[\left(\frac{\Pi_{t+1}^w}{\Pi_t^{Iw}} \right)^{\theta_t^w - 1} \mathcal{Z}_{t+1}^{w2} \right]. \tag{150}$$

Finally,

$$\mathcal{W}_t^{1-\theta_w} = \frac{1 - \gamma_w \left(\frac{\Pi_t^w}{\Pi_{t-1}^{Iw}} \right)^{\theta_w - 1}}{1 - \gamma_w}. \tag{151}$$

3.2.3 Exports demand

Export is determined by an ad-hoc demand equation

$$\frac{x_t}{x_{t-1}^{h_x}} = (P_t^{x*})_t^{-\theta_x} x_t^*, \tag{152}$$

where x_t denotes exports, P_t^{x*} is the price index of exported goods denominated in foreign currency, variable x_t^* is an exogenous shock $0 \le h_x \le 1$, $0 < \theta_x$.

3.2.4 Government

The government has balanced budget every period: purchases of public goods and pensions are financed by lump sum taxes collected from non-pensioners.

$$P_t g_t + \bar{\omega}^p P_t c_t^p = \bar{\omega}^o T_t^o. \tag{153}$$

$$P_t g_t = T_t^{no}. \tag{154}$$

3.2.5 Current account

The evolution of net foreign assets is given by

$$b_t = P_t^{x*} x_t - P_t^{m*} m_t + (1 + i_{t-1}^*) b_{t-1}. \tag{155}$$

3.2.6 Equilibrium conditions

This section discusses the equilibrium conditions and aggregation issues.

The goods market clearing conditions are

$$y_t^d = c_t + I_t + g_t + \Psi(u_t) k_t^d, \tag{156}$$
$$y_t^x = x_t + \Psi(u_t) k_t^x. \tag{157}$$

where g_t is real government consumption determined by an exogenous shock.

Equilibrium conditions of the input markets are

$$l_t = l_t^d + l_t^x, \quad m_t = m_t^d + m_t^x, \quad k_t = k_t^d + k_t^x. \tag{158}$$

3.2.7 Log-linearized model

To solve the model it is log-linearized around its steady state. This section reviews the log-linearized model equations. The tilde denotes the log-deviation of a variable from its steady-state value. Variables without time indices represent their steady-state values.

Perception on 'underlying' inflation

It is assumed that agents apply a real-time adaptive algorithm to identify their perception on the *'underlying'* inflation rate. That is, they continously update their perception by taking into account their past perception and the deviation of actual inflation to the *'perceived underlying'* one.

$$\bar{\pi}_t = \rho_\pi \bar{\pi}_{t-1} + \mathtt{g}\left(\pi_t - \bar{\pi}_{t-1}\right),$$

where $\pi_t = \widetilde{P}_t - \widetilde{P}_{t-1}$ is the observed actual, $\bar{\pi}_t = \widetilde{\bar{\Pi}}_t$ is the perceived underlying inflation rate and $0 < \rho_\pi < 1$. The gain parameter $0 < \mathtt{g} < 1$ influences the speed of learning. If one defines the cyclical component of inflation as $\hat{\pi}_t = \pi_t - \bar{\pi}_t$, then the previous formula can be expressed in the following way,

$$\bar{\pi}_t = \frac{\rho_\pi - \mathtt{g}}{1-\mathtt{g}} \bar{\pi}_{t-1} + \frac{\mathtt{g}}{1-\mathtt{g}} \hat{\pi}_t. \tag{159}$$

Aggregate demand

Combining and log-linearizing equations (138) and (139) yields the Euler equation of optimizing households'

$$\tilde{c}_t^o = \frac{h}{1+h} \tilde{c}_{t-1}^o + \frac{1}{1+h} \mathrm{E}_t\left[\tilde{c}_{t+1}^o\right] - \frac{1-h}{(1+h)\sigma} \mathrm{E}_t\left[\hat{\imath}_t - \hat{\pi}_{t+1} + d\bar{q}_{t+1}\right] + \tilde{\varepsilon}_t^c, \tag{160}$$

where, $\hat{\imath} = \tilde{\imath}_t - d\bar{e}_t$, $d\bar{e}_t$ is the preannounced rate of depreciation of the central parity of the nominal exchange rate (it is equal to zero in the crawling peg regime), and $d\bar{q}_t = d\bar{e}_t - \bar{\pi}_t$, let us call it as the *perceived average rate of real depreciation*, furthermore,

$$\tilde{\varepsilon}_t^c = \frac{(1-h)}{(1+h)\sigma}\left(\tilde{\eta}_t^c - \mathrm{E}_t\left[\tilde{\eta}_{t+1}^c\right]\right).$$

Log-linearizing equations (143) and (154) yields the following formula,

$$\tilde{c}_t^{no} = \widetilde{w}_t + \tilde{l}_t. \tag{161}$$

Equation (144) implies that expression

$$\tilde{c}^p = \widetilde{w}_t/2 \tag{162}$$

describes the evolution of log-linearized consumption of pensioners. Path of aggregate consumption is determined by

$$\tilde{c}_t = \omega^o \tilde{c}_t^o + \omega^{no} \tilde{c}_t^{no} + \omega^p \tilde{c}_t^p, \tag{163}$$

where $\omega^j = c^j \bar{\omega}^j / c$, $j = o, no, p$.

In *Appendix B.1.3* it is shown that the log-linearized version of equation (141) is

$$\begin{aligned}\mathrm{E}_t\left[\hat{\imath}_t - \hat{\pi}_{t+1} + d\bar{q}_{t+1}\right] &= \frac{1-\delta}{1-\delta+r^k} \mathrm{E}_t\left[\widetilde{Q}_{t+1}\right] - \widetilde{Q}_t \\ &+ \frac{r^k}{1-\delta+r^k} \mathrm{E}_t\left[\tilde{r}_{t+1}^k\right] + \tilde{\varepsilon}_t^Q.\end{aligned} \tag{164}$$

Appendix B.1.3 explains how to derive from equation (140) the following log-linear formula determining the trajectory of investments.

$$\tilde{I}_t = \frac{1}{1+\beta}\tilde{I}_{t-1} + \frac{\beta}{1+\beta}\mathrm{E}_t\left[\tilde{I}_{t+1}\right] + \frac{1}{(1+\beta)\phi_I}\widetilde{Q}_t + \tilde{\varepsilon}_t^I, \tag{165}$$

where

$$\tilde{\varepsilon}_t^I = \frac{\beta\mathrm{E}_t\left[\tilde{\eta}_{t+1}^I\right] - \tilde{\eta}_t^I}{1+\beta}.$$

Capital accumulation equation is standard.

$$\tilde{k}_{t+1} = (1-\delta)\tilde{k}_t + \delta\tilde{I}_t + \tilde{\varepsilon}_t^k. \tag{166}$$

The log-linear version of the export-demand equation (152) is

$$\tilde{x}_t = h_x\tilde{x}_{t-1} - \theta_x\tilde{P}_t^{x*} + \tilde{x}_t^*. \tag{167}$$

Log-linearizing the equilibrium conditions (156) and (157) yields [38]

$$y^d\tilde{y}_t^d = c\tilde{c}_t + I\tilde{I}_t + g\tilde{g}_t + r^k k^d\psi\tilde{r}_t^k, \tag{168}$$

$$y^x\tilde{y}_t^x = x\tilde{x}_t + r^k k^x\psi\tilde{r}_t^k, \tag{169}$$

recall that $\psi = \Psi'(1)/\Psi''(1)$.

Aggregate supply

In *Appendix B.1.1* it is shown that *demand for production inputs* is represented by the following log-linear equations,

$$\begin{aligned} \tilde{k}_t^s &= \varrho(1-\alpha_s)\left(\widetilde{w}_t^{zs} - \tilde{r}_t^k\right) - \psi\tilde{r}_t^k + \frac{\tilde{y^s}_t}{1+f_s} - \widetilde{A}_t, \qquad s = d,\, x, \\ k\tilde{k}_t &= k^d\tilde{k}_t^d + k^x\tilde{k}_t^x. \end{aligned} \tag{170}$$

where $f^s = \bar{f}^s/y$, and the second line is a consequence of the third equilibrium condition of formula (158).

$$\begin{aligned} \widetilde{w}_t^{zs} &= a_s\widetilde{w}_t + (1-a_s)\left(\tilde{q}_t + \widetilde{P}_t^{m*}\right) + \phi_z\tilde{z}_t^s, \qquad s = d,\, x. \\ \tilde{q}_t &= \tilde{e}_t - \widetilde{P}_t, \end{aligned}$$

α_s is the steady-state share of capital in production cost, that is,

$$\alpha_s = \frac{r^k k^s}{mc^s\left(y^s + \bar{f}_s\right)}, \qquad s = d,\, x,$$

and a_s is the steady-state share of labor in w^{zs}, that is,

$$a_s = \frac{wl^s}{w^{zs}z^s}, \qquad s = d,\, x.$$

[38] Equation (142) implies that $\Psi'(1) = r_k$ and $\tilde{u}_t = \tilde{r}_t^k\Psi'(1)/\Psi''(1)$.

Furthermore,

$$
\begin{aligned}
\tilde{l}_t^s &= \varrho_z(1-a_s)\left(\tilde{q}_t + \widetilde{P}_t^{m*} - \widetilde{w}_t\right) + \tilde{z}_t^s, \qquad s = d,\, x, \\
l\tilde{l}_t &= l^d \tilde{l}_t^d + l^x \tilde{l}_t^x, && (171)
\end{aligned}
$$

and

$$
\begin{aligned}
\widetilde{m}_t^s &= \varrho_z a_s \left(\widetilde{w}_t - \tilde{q}_t - \widetilde{P}_t^{m*}\right) + \tilde{z}_t^s, \qquad s = d, x, \\
m\widetilde{m}_t &= m^d \widetilde{m}_t^d + m^x \widetilde{m}_t^x, && (172)
\end{aligned}
$$

where

$$
\tilde{z}_t^s = \varrho\alpha_s\left(\tilde{r}_t^k - \widetilde{w}_t^{zs}\right) + \frac{\tilde{y^s}_t}{1+f_s} - \widetilde{A}_t, \qquad s = d,\, x,
$$

and the equilibrium conditions of formula (158) are used again.

It is shown in *Appendix B.1.2* that the Calvo price-setting rule with indexation to lagged inflation implies the following log-linear *hybrid Phillips curve.*

$$
\begin{aligned}
\hat{\pi}_t &= \frac{\beta}{1+\beta\vartheta_d}\mathrm{E}_t\left[\hat{\pi}_{t+1}\right] + \frac{\vartheta_d}{1+\beta\vartheta_d}\hat{\pi}_{t-1} && (173) \\
&+ \frac{\xi_d}{1+\beta\vartheta_d}\left[\alpha_d\tilde{r}_t^k + (1-\alpha_d)\widetilde{w}_t^{zd} - \widetilde{A}_t\right] + \tilde{\upsilon}_t^d,
\end{aligned}
$$

where

$$
\xi_d = \frac{(1-\gamma_d)(1-\beta\gamma_d)}{\gamma_d}, \qquad \tilde{\upsilon}_t = -\frac{\xi_d}{1+\beta\vartheta_d}\tilde{\tau}_t.
$$

The *Phillips curve* of the exports sector is given by

$$
\begin{aligned}
\hat{\pi}_t^{x*} &= \frac{\beta}{1+\beta\vartheta_d}\mathrm{E}_t\left[\hat{\pi}_{t+1}^{x*}\right] + \frac{\vartheta_x}{1+\beta\vartheta_x}\hat{\pi}_{t-1}^{x*} && (174) \\
&+ \frac{\xi_x}{1+\beta\vartheta_x}\left[\alpha_x\tilde{r}_t^k + (1-\alpha_x)a_x\widetilde{w}_t - \left[\alpha_x - (1-\alpha_x)a_x\right]\tilde{q}_t + (1-\alpha_x)(1-a_x)\widetilde{P}_t^{m*}\right] \\
&+ \frac{\xi_x}{1+\beta\vartheta_x}\left[(1-\alpha_x)\phi_z\tilde{z}_t^x - \widetilde{P}_t^{x*} - \widetilde{A}_t\right] + \tilde{\upsilon}_t^x,
\end{aligned}
$$

where $\hat{\pi}_t^{x*} = \pi_t^{x*} - \bar{\pi}_t^{x*}$, $\pi_t^{x*} = \widetilde{P}_t^{x*} - \widetilde{P}_{t-1}^{x*}$ and

$$
\xi_x = \frac{(1-\gamma_x)(1-\beta\gamma_x)}{\gamma_x}, \qquad \tilde{\upsilon}_t^x = -\frac{\xi_x}{1+\beta\vartheta_x}\tilde{\tau}_t^x.
$$

Wage setting in the model is based on similar assumptions as price formation. *Appendix B.1.4* shows that the log-linear *wage Phillips curve* is given by

$$
\begin{aligned}
\hat{\pi}_t^w &= \frac{\beta}{1+\beta\vartheta_w}\mathrm{E}_t\left[\hat{\pi}_{t+1}^w\right] + \frac{\vartheta_w}{1+\beta\vartheta_w}\hat{\pi}_{t-1}^w && (175) \\
&+ \frac{\xi_w}{1+\beta\vartheta_w}\left[\frac{\sigma}{1-h}\left(\tilde{c}_t^l - h\tilde{c}_{t-1}^l\right) + \varphi\tilde{l}_t - \widetilde{w}_t\right] + \tilde{\upsilon}_t^w,
\end{aligned}
$$

where

$$\xi_w = \frac{(1-\gamma_w)(1-\beta\gamma_w)}{\gamma_w(1+\theta_w\varphi)}, \qquad \tilde{\upsilon}_t = \frac{\xi_w}{1+\beta\vartheta_w}\left(\eta_t^l - \tau_t^w\right)$$

and

$$\tilde{c}_t^l = \frac{\omega^o\left(c^o\right)^{-\sigma-1}\tilde{c}_t^o + \omega^{no}\left(c^{no}\right)^{-\sigma-1}\tilde{c}_t^{no}}{\omega^o\left(c^o\right)^{-\sigma-1} + \omega^{no}\left(c^{no}\right)^{-\sigma-1}},$$

furthermore,

$$\hat{\pi}_t^w = \widetilde{w}_t - \widetilde{w}_{t-1} + \hat{\pi}_t. \tag{176}$$

Current account

Equation (155) implies that

$$\tilde{b}_t = (1+i^*)\tilde{b}_t + \frac{P^{x*}x}{GDP^*}\left(\widetilde{P}_t^{x*} + \tilde{x}_t\right) - \frac{P^{m*}m}{GDP^*}\left(\widetilde{P}_t^{m*} + \widetilde{m}_t\right), \tag{177}$$

since it is assumed that $b = 0$, $\tilde{b}_t = b_t/GDP^*$, where $GDP^* = Py^d/e + P^{x*} - P^{m*}m$.

The interest rate and the exchange rate

Decomposing nominal depreciation of the nominal exchange rate gives:

$$\tilde{e}_t - \tilde{e}_{t-1} = d\bar{e}_t + d\hat{e}_t = d\bar{e}_t + \hat{e}_t - \hat{e}_{t-1},$$

where $d\bar{e}_t$ is the exogenously given deterministic part of depreciation and $\hat{e}_t$ is the cyclical part of the nominal exchange rate. In the crawling-peg regime it is assumed that $d\bar{e}_t$ is the announced rate of the crawl, in the inflation-targeting regime $d\bar{e}_t = 0$.

Uncovered interest rate parity with financial premium shock can be expressed as

$$\hat{\imath}_t = \mathrm{E}_t\left[d\hat{e}_{t+1}\right] + \tilde{\imath}_t^* + \tilde{\varepsilon}_t^{pr}, \tag{178}$$

following Schmitt-Grohe and Uribe (2002), it is assumed that $\tilde{\imath}_t^* = -\nu\tilde{b}_t$, this assumption ensures stationary of $\tilde{b}_t$.

Let assume that in the crawling-peg regime the main focus of monetary policy is determination of the rate of crawl. Hence the behavior of cyclical part of the nominal interest rate is captured by the following simple equation.

$$\hat{\imath}_t = \zeta_e^{cr}\hat{e}_t + \tilde{\varepsilon}_t^r, \tag{179}$$

where $\tilde{\varepsilon}_t^r$ is an exogenous stochastic shock, and $\zeta_e^{cr} > 0$ ensures that $\hat{e}_t$ is stationary. Since the presence of ζ_e^{cr} is due to this technical requirement its magnitude is set to be negligible.

In the inflation-targeting regime the behavior of the monetary authority is captured by the following *interest-rate rule*.

$$\hat{\imath}_t = \zeta_i\hat{\imath}_{t_1} + (1-\zeta_i)\left[\zeta_\pi\left(\hat{\pi}_t - d\bar{q}_t\right) + \zeta_e^{it}\hat{e}_t\right] + \tilde{\varepsilon}_t^r. \tag{180}$$

Recall that $-d\bar{q}_t = \bar{\pi}_t$ in the inflation targeting regime. Again, the only role of $\zeta_e^{it} > 0$ is to ensure the stationarity of $\hat{e}_t$.

The domestic component of the real exchange rate is determined by the following identity.

$$\tilde{q}_t - \tilde{q}_{t-1} = d\hat{e}_t - \hat{\pi}_t + d\bar{q}_t. \tag{181}$$

Finally equation (159) implies the following law of motion for $d\bar{q}_t = d\bar{e}_t - \bar{\pi}_t$,

$$d\bar{q}_t = \frac{\rho_\pi - \mathsf{g}}{1-\mathsf{g}} d\bar{q}_{t-1} - \frac{\mathsf{g}}{1-\mathsf{g}} \hat{\pi}_t + \tilde{\chi}_t, \tag{182}$$

where

$$\tilde{\chi}_t = d\bar{e}_t - \frac{\rho_\pi - \mathsf{g}}{1-\mathsf{g}} d\bar{e}_{t-1}$$

is an exogenous shock.

Complementary employment equation

Since there is no consistent data available on aggregate hours worked for Hungary, employment data are used instead. Hence, following Adolfson et al. (2006) and Smets and Wouters (2003), the model is complemented by the following Calvo-type *measurement equation* for *employment*.

$$\Delta\tilde{n}_t = \beta \mathrm{E}_t \left[\Delta\tilde{n}_{t+1}\right] + \frac{(1-\gamma_n)(1-\beta\gamma_n)}{\gamma_n} \left(\tilde{l}_t - \tilde{n}_t\right) + \tilde{\varepsilon}_t^n, \tag{183}$$

where $\Delta\tilde{n}_t = \tilde{n}_t - \tilde{n}_{t-1}$, $\tilde{n}_t$ denotes the number of people employed at date t, and γ_n is a parameter and $\tilde{\varepsilon}_t^n$ is an error term.[39]

Summary

The behavior of the crawling-peg regime is captured by a 23-equation system of formulas (160) – (179) and (181) – (183). It determines the trajectories of 23 endogenous variables, namely, $\hat{\pi}_t$, $\hat{\pi}_t^{x*}$, $\hat{\pi}_t^w$, $\tilde{y}_t^d$, $\tilde{y}_t^x$, $\tilde{c}_t$, $\tilde{c}_t^o$, $\tilde{c}_t^{no}$, $\tilde{c}_t^p$, $\widetilde{w}_t$, $\tilde{x}_t$, $\widetilde{m}_t$, $\tilde{l}_t$, $\tilde{n}_t$, $\tilde{k}_t$, $\tilde{I}_t$, $\tilde{q}_t$, $d\bar{q}_t$, $\hat{e}_t$, $\hat{\imath}_t$, $\tilde{b}_t$, $\widetilde{Q}_t$, and $\tilde{r}_t^k$. The system is driven by 15 exogenous shocks, $\tilde{g}_t$, $\widetilde{P}_t^{m*}$, $\tilde{\chi}_t$, $\tilde{x}_t^*$, $\widetilde{A}_t$, $\tilde{\upsilon}_t^d$, $\tilde{\upsilon}_t^w$, $\tilde{\upsilon}_t^x$, $\tilde{\varepsilon}_t^c$, $\tilde{\varepsilon}_t^k$, $\tilde{\varepsilon}_t^r$, $\tilde{\varepsilon}_t^{pr}$, $\tilde{\varepsilon}_t^n$, $\tilde{\varepsilon}_t^I$ and $\tilde{\varepsilon}_t^Q$.

The inflation-targeting regime is described by equations (160) – (178) and (180) – (183). This set of equations determines the same 23 endogenous variables. The system is driven by the same 15 shocks as previously.

3.3 Bayesian Estimation

In order to estimate the parameters of the DSGE model presented in *Section 3.2* quarterly Hungarian data of thirteen macroeconomic variables is used: real consumption, real investments, real exports, real imports, real government consumption, real wages, employment, capital stock, CPI inflation rate, nominal

[39] Smets and Wouters applied first a similar employment equation in their estimated model. The particular form of equation (183) is taken from Adolfson et al. Equation (37) of Smets and Wouters is slightly different. It contains terms $\tilde{n}_t$ and $\tilde{n}_{t+1}$ instead of $\Delta\tilde{n}_t$ and $\Delta\tilde{n}_{t+1}$.

interest rate, import and export prices denominated in foreign currency and the preannounced rate of the nominal-exchange-rate crawl. Estimation is based on the database of the Quarterly Projection Model of the Magyar Nemzeti Bank (data set presented in Benk et al. (2006)). This covers the period of 1995:2-2007:2. Detailed description of the data and the applied data transformations can be found in *Appendix B.4*.

To estimate the model, a likelihood-based Bayesian method described in An and Schorfheide (2005) is applied. The first step is to construct the likelihood function. This needs the reduced form rational-expectations solution. Then one has to write the model in its state-space form, and formulate the Kalman filter for calculating the likelihood function. The construction of the Kalman filter is described in detail in *Appendix B.3*. In the next step, the likelihood function is combined with prior distributions in order to derive the posterior density function of parameters. Then one has to find numerically the mode of the posterior density function. Finally, the random-walk Metropolis-Hastings (MH) algorithm is used to generate the posterior distribution. The applied MH algorithm is based on 500,000 draws (2 parallel chains of 250,000 draws discarding the initial burn-in period of 50,000 iterations). To monitor the convergence of the MH algorithm the method of Brooks and Gelman (1998) is applied.[40] In order to compare different model versions, the marginal likelihoods of models are calculated by the modified harmonic mean algorithm of Geweke (1998).

In the studied time period there is one obvious structural break: in 2001 the crawling-peg regime was abandoned and inflation targeting was introduced. To capture this change in monetary policy practice two different policy rules in the two subperiods is estimated, as was discussed in the previous section. The estimation procedure also allowed some other parameters to change between the two regimes. Namely, price setting parameters and parameters of the financial premium and the labor market shock are time varying.[41]

3.3.1 Calibrated and fixed parameters

Some parameters are not estimated but kept fixed from the start of the procedure (see *Table 3.1*). This can be viewed as a very strict prior.

First, the standard-deviation and autoregressive parameters of exogenous shock with observable time series was estimated, (namely, the government-spending $\tilde{g}_t$, the measurement error of capital accumulation $\tilde{\varepsilon}_t^k$ and the import-price $\widetilde{P}_t^{m*}$ shocks) by single-equation OLS. Then these results are fixed throughout the estimation procedure of the full system.

Second, the time series of the deterministic part of depreciation $d\bar{e}_t$ was constructed. Using the constructed time series the standard-deviation and au-

[40] For the numerical implementation of the estimation procedure we developed our own MATLAB code. Reduced form RE solutions were calculated by the MATLAB routine of Uhlig (1999). For finding the mode of a posterior distribution, we used the algorithm and code of Kuntsevich and Kappel (1997).

[41] There is a vast literature that the rigidity of prices and wages depends on monetary-policy regimes, see, e.g., Taylor (2000)).

toregressive parameters of this shock was estimated by OLS.

Third, some other parameters can be directly related to the steady-state values of endogenous variables. These are the production function parameters, the subjective discount rate of households, depreciation rate and the elasticity-of-substitution between varieties of differentiated goods and that of differentiated labor.

Fourth, there were parameters which were not able to be identified. Concretely, the algorithm of searching the mode of the posterior density function failed if these parameters were not fixed. To identify these parameters values common in the business cycle literature were chosen. The exception is the adjustment-cost parameters of investments Φ'' and that of the import-labor boundle.Φ_z''. Several values were picked, and the accompanying marginal likelihoods of the different estimated model versions were compared. The parameter value with the highest marginal likelihood was then selected (although large differences between the different versions were not found). Finally, adjustment of capital ($\Phi'' = 13$) turned out to be relatively high compared to international estimates. A more moderate adjustment cost for the labor-import boundle ($\Phi_z'' = 3$) was selected.

The share of non-optimizing households ($1-\omega^{no}$) was set to be 0.25, based on some survey evidence stating that 25 per cent of Hungarian households do not have connections with the banking sector. The share of pensioners among non-optimizers (ω^p) was determined by a regression such that income of pensioners equals to half of real wage according to the *'Swiss-index-formula'* determining real pensions in Hungary. The production function parameters ϱ and ϱ_z were calibrated, in such a way that imports and labor are complements and capital and the import-labor bundle has an elasticity of transformation of 0.8, as estimated by Kátay and Wolf (2005).

Finally, parameters ζ_e^{cr}, ζ_e^{it} and ν are technical parameters, their only role is to assure stationarity of the model. Therefore small values were chosen for these coefficients.

Table 3.1 Fixed parameter values

Parameter		
Name		Value
standard error of gov't. consumption	σ_g	4.72
standard error of import prices	$\sigma_{p^{m*}}$	2.19
standard error of χ_t	σ_χ	0.12
standard error of capital measurement error	σ_k	0.15
autoreg. coeff. of gov't. consumption	ρ_g	0.46
autoreg. coeff. of import prices	$\rho_{p^{m*}}$	0.74
autoreg. coeff. of χ_t	ρ_χ	0.53
autoreg. coeff of capital measurement error	ρ_k	0.60
autoreg. coeff of perceived average inflation	$\rho_{\bar{\pi}}$	0.99
discount factor	β	0.99
steady-state share of capital in real marginal costs, domestic	α_d	0.17
steady-state share of capital in real marginal costs, export	α_d	0.14
steady-state share of labor in w_t^z,domestic	a_d	0.50
steady-state share of labor in w_t^z, export	a_x	0.36
depreciation rate	δ	0.025
elasticity of subt. of goods	θ	6.00
elasticity of subt. of labor	θ_w	3.00
fraction of optimizing households's consumption	$1-\omega^{no}$	0.75
fraction of pensioners' consumption in total non-optimizer consumption	ω^p/ω^{no}	0.35
disutility parameter of labour	φ	8.00
Calvo parameter of employment	γ_n	0.70
elasticity of subt. between capital and z	ϱ	0.80
elasticity of subt. between labor and import	ϱ_z	0.50
ratio of fixed cost relative to total output	$\bar{f}_{d,}\ \bar{f}_x$	0.20
capacity utilization adj. cost	ψ	0.20
investments adjustment cost	Φ''	13.00
labour-import utilization adjustment cost	Φ''_z	3.00
exchange rate elasticity of the policy rule	ζ_e^{cr}	0.001
exchange rate elasticity of the policy rule	ζ_e^{it}	0.025
debt elasticity of financial premium	ν	0.001

3.3.2 Specifying prior distributions

Prior distributions for parameters of non-observed exogenous shocks are displayed in *Table 3.2*. All the standard deviations of the shocks are assumed to be distributed as an inverted Gamma distribution with a degree of freedom equal to 2. This distribution guarantees a positive standard deviation with a rather large domain. Prior distributions of autoregressive parameters are assumed to follow Beta distributions with mean of 0.8 and standard error of 0.1.

Prior distributions for the rest of estimated parameters are shown in *Table 3.3*. Calvo parameters of consumer and export price setting and that of nominal wages were set to be equal for both regimes with a relatively uninformative prior, a Beta distribution with mean of 0.5 and standard error of 0.2. Similarly, indexation parameters (ϑ_p, ϑ_x and ϑ_w) also received a not very tight prior of Beta with standard deviation of 0.2 and mean of 0.6.

The choice of prior for the parameter of interest rate smoothing ζ_i is different to the literature. A relatively uninformative Uniform prior was imposed on the distribution on it. Our prior for the learning gain (g) paramer was relatively tight, a Beta distribution with mean of one-sixth and standard error of 0.03. Due to some stylized evidence on low real-interest-rate elasticity of consumption in Hungary, a mean value for parameter σ higher than that of Smets and Wouters (2003) was chosen .

Prior distributions for the rest of the parameters were chosen similarly to Smets and Wouters (2003).

3.3.3 Estimation results

As was mentioned, different values for some parameters was estimated for the crawling-peg and the inflation-targeting periods, namely for the standard-deviation and autoregressive parameters of shocks $\tilde{\upsilon}_t^w$ and $\tilde{\varepsilon}_t^{pr}$, and the Calvo and indexation parameters, (γ_p, γ_x, γ_w, ϑ_p, ϑ_x and ϑ_w). Their different values are denoted by superscripts *cr* and *it*, respectively. Recall, that σ_{de} belongs to the nominal-exchange rate shock of the crawling-peg regime, and σ_r, ζ_i, and ζ_π belong to the the policy-rule equation of the inflation-targeting period. Estimation results are summarized in *Tables 3.2* and *3.3*.

None of the estimated values of the Calvo parameters are very different in the two monetary policy regimes. This seems surprising at the first glance as one would assume a change in these key parameters of Phillips curves. As shown later, the regime change had rather an effect on the indexation behavior. The Calvo-parameters of domestic prices are close to that of euro-area estimates, see, e.g., Smets and Wouters (2003, SW) and the *new area wide model* (NAWM) of the ECB, described in Christoffel et al. (2007). Export prices are estimated to be less sticky than consumer prices. This conforms to the intuition that exporters in Hungary mostly produce intermediate goods with probably less relevant price stickiness. There is a significant difference with respect to the Calvo parameters of wages: in Hungary nominal wages are estimated to be less sticky than in the eurozone. In addition, wages are estimated to be more flexible than either consumer or export prices.

Unlike Calvo coefficients, the monetary regime shift is mostly felt in the indexation properties in pricing (indexation of consumer prices dropped in the second regime). This migh indicate that the crawling-peg regime served as a natural way for indexation-mechanisms. Indexation parameter of consumer prices in the inflation targeting regime is lower than that of Christoffel et al. (2007), but comparable to that in Smets and Wouters (2003). That is, their no consensus on the issue of price indexation in the literature. As far as nominal wage indexation is concerned, it is much lower than in NAWM and in Smets and Wouters (2003) in both monetary regimes.

However, it is important to note that one should be cautious to interpret our results of price and wage indexation. Indexation formulas reveal that in this both prices and wages are fully indexed to the perceived underlying component of inflation. Besides that, the parameters ϑ_p and ϑ_w represent the degree of additional indexation to the cyclical components of past price and wage inflation rates.

The mean speed of learning the *'perceived underlying inflation'* (g) is estimated to be higher than the prior mean.

In estimated US and euro-area models the value of the interest-rate-smoothing parameter ζ_i is quite high.[42] On the other hand, a relatively low value around 0.75 is estimated. It is important to note that this result also contrasts with previous Hungarian estimates. For example, Hidi (2006) in his estimated single-equation policy rule found a much higher interest-rate smoothing parameter comparable with the values in the international literature. Goodhart (2004) shows a possible explanation for this, he argues that non-structural single-equation methods overestimates the value of interest-rate smoothing parameter, since they are not able to identify some persistent structural shocks influencing the behavior of the policy rate.

As mentioned earlier, the adjustment cost of investment was chosen at a value higher than usually estimated in other DSGE models. In addition, the presence of cost of adjustment for labor-import boundle is not usually assumed in the literature.

Comparing posterior and prior density graphs, data were informative, prior and posterior density graphs differ, the only exceptions are the export price elasticity and the export smoothing parameters (θ_x and h_x) where prior and posterior distributions are close to each other (see *Appendix B.5*).

[42] See CEE, SW, NAWM,. Flat prior Rabanal and Rubio-Ramirez, Világi (2007)

Table 3.2 Estimated parameters of exogenous shocks

		Prior distribution			Estimated posterior		
				Stand.			90%
		Type	Mean	err.	Mode	Mean	prob. int.
Standard errors							
productivity	σ_A	I.Gam.	0.5	2*	2.080	2.152	$[1.82, 2.55]$
export demand	σ_x	I.Gam.	0.5	2*	2.352	2.464	$[2.06, 2.95]$
cons. pref.	σ_c	I.Gam.	0.5	2*	0.146	0.203	$[0.11, 0.33]$
cons. price markup	σ_p	I.Gam.	0.5	2*	0.397	0.420	$[0.34, 0.52]$
export price markup	σ_{px}	I.Gam.	0.5	2*	1.873	2.182	$[1.64, 2.87]$
labor market	σ_w^{cr}	I.Gam.	0.5	2*	0.824	0.922	$[0.65, 1.26]$
labor market	σ_w^{it}	I.Gam.	0.5	2*	0.609	0.932	$[0.54, 1.42]$
investments	σ_I	I.Gam.	0.5	2*	0.969	1.003	$[0.76, 1.27]$
Equity premium	σ_Q	I.Gam.	0.5	2*	0.167	0.393	$[0.11, 0.99]$
policy rule	σ_r^{cr}	I.Gam.	0.5	2*	0.574	0.602	$[0.48, 0.76]$
policy rule	σ_r^{it}	I.Gam.	0.5	2*	0.229	0.247	$[0.19, 0.32]$
fin. premium	σ_{pr}^{cr}	I.Gam.	0.5	2*	0.221	0.372	$[0.17, 0.67]$
fin. premium	σ_{pr}^{it}	I.Gam.	0.5	2*	0.486	0.666	$[0.36, 1.06]$
employment	σ_n	I.Gam.	0.5	2*	0.369	0.383	$[0.30, 0.49]$
Autoregressive coefficients							
productivity	ρ_A	Beta	0.8	0.1	0.577	0.552	$[0.43, 0.68]$
export demand	ρ_x	Beta	0.8	0.1	0.616	0.625	$[0.51, 0.73]$
cons. pref.	ρ_c	Beta	0.8	0.1	0.833	0.767	$[0.60, 0.88]$
labor market	ρ_w^{cr}	Beta	0.8	0.1	0.486	0.480	$[0.32, 0.64]$
labor market	ρ_w^{it}	Beta	0.8	0.1	0.797	0.661	$[0.43, 0.87]$
export markup	ρ_x	Beta	0.5	0.15	0.317	0.318	$[0.15, 0.50]$
investments	ρ_I	Beta	0.8	0.1	0.497	0.488	$[0.33, 0.65]$
fin. premium	ρ_{pr}^{cr}	Beta	0.8	0.1	0.899	0.833	$[0.69, 0.93]$
fin. premium	ρ_{pr}^{it}	Beta	0.8	0.1	0.872	0.820	$[0.70, 0.92]$
employment	ρ_n	Beta	0.8	0.1	0.790	0.770	$[0.64, 0.89]$

* For the Inverted Gamma function the degrees of freedom are indicated.

Table 3.3 Estimated parameters

		Prior distribution			Estimated posterior		
				Stand.			90%
		Type	Mean	err.	Mode	Mean	prob. int.
Utility function parameters							
consumption	σ	Norm.	2.00	0.40	1.680	1.814	$[1.18, 2.46]$
habit	h	Beta	0.75	0.15	0.597	0.646	$[0.45, 0.83]$
Price and wage setting param.							
ind. cons. prices	ϑ_p^{cr}	Beta	0.60	0.20	0.873	0.821	$[0.63, 0.96]$
ind. cons. prices	ϑ_p^{it}	Beta	0.60	0.20	0.416	0.431	$[0.22, 0.66]$
ind. exp. prices	ϑ_x^{cr}	Beta	0.60	0.20	0.215	0.290	$[0.10, 0.55]$
ind. exp. prices	ϑ_x^{it}	Beta	0.60	0.20	0.383	0.494	$[0.18, 0.83]$
ind. wages	ϑ_w^{cr}	Beta	0.60	0.20	0.112	0.169	$[0.05, 0.34]$
ind. wages	ϑ_w^{it}	Beta	0.60	0.20	0.107	0.185	$[0.05, 0.40]$
Calvo cons. prices	γ_p^{cr}	Beta	0.50	0.20	0.939	0.938	$[0.92, 0.96]$
Calvo cons. prices	γ_p^{it}	Beta	0.50	0.20	0.929	0.921	$[0.88, 0.95]$
Calvo exp. prices	γ_x^{cr}	Beta	0.50	0.20	0.850	0.824	$[0.75, 0.89]$
Calvo exp. prices	γ_x^{it}	Beta	0.50	0.20	0.827	0.810	$[0.73, 0.89]$
Calvo wages	γ_w^{cr}	Beta	0.50	0.20	0.714	0.698	$[0.58, 0.81]$
Calvo wages	γ_w^{it}	Beta	0.50	0.20	0.711	0.657	$[0.46, 0.88]$
Other parameters							
exp. elasticity	θ_x	Beta	0.50	0.10	0.510	0.534	$[0.40, 0.67]$
exp. smooth.	h_x	Beta	0.75	0.15	0.503	0.507	$[0.35, 0.66]$
ir. smooth.	ζ_i	U(0,1)	0.50	0.29	0.766	0.761	$[0.67, 0.84]$
policy rule	ζ_π	Norm.	1.50	0.16	1.375	1.379	$[1.12, 1.65]$
gain	g	Beta	0.167	0.03	0.229	0.234	$[0.17, 0.30]$

3.4 Analysis of structural shocks and perceived underlying inflation

There are fifteen structural shocks determining the economy. Two of them, $\tilde{g}_t$ and $\widetilde{P}_t^{m*}$, are observable, and one, the measurement error for capital accumulation ($\tilde{\varepsilon}_t^k$) was estimated from an OLS estimate *Figure 3.1* displays the three exogenous series. The deterministic part of depreciation, $d\bar{e}_t$, is also treated as an exogenous shock in the estimation exercise, it equals to the rate of crawl in the crawling-peg regime, and captures a one-off trend appreciation after the introduction of the new exchange rate regime accompanied by a widening of the intervention band. (see *Figure 3.2*)

The rest of the shock are unobservable, and they are treated as latent variables in the estimation procedure, and calculated by the two-sided Kalman-smoother. The analysis of this section based on shock trajectories belonging to a model version parameterized by the estimated mean values of the inflation-targeting period.

Figure 3.2 shows the estimated trajectories of shock directly influencing the nominal interest rate and the nominal exchange rate. Namely, the nominal depreciation shock in the crawling-peg regime, $\tilde{\chi}_t$, the monetary-policy shock of the inflation-targeting period, $\tilde{\varepsilon}_t^r$, and the financial-premium shock in the uncovered-interest-rate-parity equation, $\tilde{\varepsilon}^{pr}$. Since foreign-interest-rate series is not used in the estimation procedure the estimated financial-premium shock incorporates foreign-interest-rate movements, as well.

The evolution of the above shocks fits some well-documented events of the

Hungarian economy of the past decade. Credibility in the exchange rate regime was somewhat weak at the outset of the crawling peg regime (in 1996) and this is reflected in the financial premium shock. In addition the change in monetary regime in 2001, accompanied by a significant appreciation of the Hungarian forint, can also be clearly observed as a series of negative shocks. To interpret this, one can also think of this shock mirroring the substantial change in portfolios (i.e. an increase in forint denominated government debt among the assets of international investors). A period of increasing risk of Hungarian assets is demonstrated also in 2003, when the central parity was devalued and the forint depreciated markedly as financial markets became vulnerable. The appreciating speculation in early 2003 is also shown as a negative premium shock. The shock also describes the gradual tightening of the ECB at the end of the sample. Moreover, in the summer of 2006 exchange rate depreciated after the announcement of the fiscal stabilization and this shows up in a temporary financial premium shock as the reaction of monetary policy was relatively smooth and exchange rate only strengthened back to the pre-stabilization levels later.

The estimated trajectories of the rest of the shocks can be seen in *Figure 3.3*. The export-demand shock, $\hat{x}_t^*$, also matches to common perception of the economy: the slowdown in Europe because of Russian crisis and financial market evolutions in US in 1998 and 1999 and the sluggish demand for exports between 2002-2003. It also shows a gradual recovery at the end of the sample.

The consumer preference shock, $\tilde{\varepsilon}_t^c$, shows the effects of the fiscal stimulus during 2002 and 2003. In contrast to the observed government spending shock, this shock mostly captures indirect effects of fiscal policy, namely, rise in transfers and the easing of household mortgage subsidies. One could also explain the rise in consumer prefence as a result of wealth effects generated by the fiscal policy, as well. In addition, the deepening of financial markets can also account for this rise.[43] The model detects a strong negative preference shock after the fiscal consolidation package introduced in 2006.

The price markup shock $\tilde{v}_t$ is relatively volatile, but some part of the Hungarian inflation history can be realized. For example, the drop in price markup in early 1999 might be the result of a decrease of unprocessed food, oil and import prices due to the Russian crisis. On the other hand, a rise in food prices also captured by the estimated shock just before the introduction of the inflation targeting regime in 2001. A VAT-hike in 2004 is also detected by the model as a markup shock. Price markup started to decline after 2004, which might be the consequence of growing competition in retail sector due to Hungary's accession to the EU. The effects of fiscal consolidation accompanied by VAT and regulated price hikes in 2006 are also estimated as price markup shock.

The labor-market shock $\tilde{v}_t^w$ is a combination of two structural shocks, a labor-supply shock and a wage-markup shock. *Figure 3.3* reveals that this shock is heteroskedastic in the sample, the variance of the shock increased in the inflation-targeting regime. Nominal wages were severely perturbed by gov-

[43] Since 2001, credits to households started to accelerate and part of this might be explained by widening access to financial instruments. Liquidity constraints continuously eased.

ernment measures in this period. The effects of minimum wage hikes in 2001, 2002 and 2006 was detected by the model. Adjustment of nominal wages to the new low inflation environment after the introduction of the more disinflation oriented inflation-targeting system might have also created large nominal wage fluctuations. In 2004 and 2006, when the VAT was hiked, a negative labor-market shock can be observed, this might point to the fact that the increase in tax-wedge was not translated into higher wages that time. On the other hand, the coincidence of wage and price markup shocks might point to some specification problems, as well. This might call for a more precise modelling of labor markets e.g. as tried by Jakab and Kónya (2008).

The evolution of the productivity shock $\widetilde{A}_t$, predicts a slowdown in productivity during 1997 and 2001 and a higher productivity era since 2002. This is in contrast with other micro-level data based estimates (e.g. Convergence Report (2006) or Benk et al (2005)). The latter studies argue that at the end of the sample a slowdown in productivity occurred. However, these studies measures labor as employment, while in this model hours enter into production function. Hence, the difference between the model's productivity measure and the one estimated by e.g. Benk et al (2005) might contain the possibly different evolution of hours and employment.

In summary: in most cases the estimated shocks conform to the documented special events of the Hungarian and world economy. However, the productivity and the labor-market shocks might indicate the presence of events not captured by this model. The treatment of hours and capital as latent variables and the heteroskedasticity of labour market shock are worth analyzing more deeply in the future.

Figure 3.1 Government spending, import-price and capital measurement error shocks

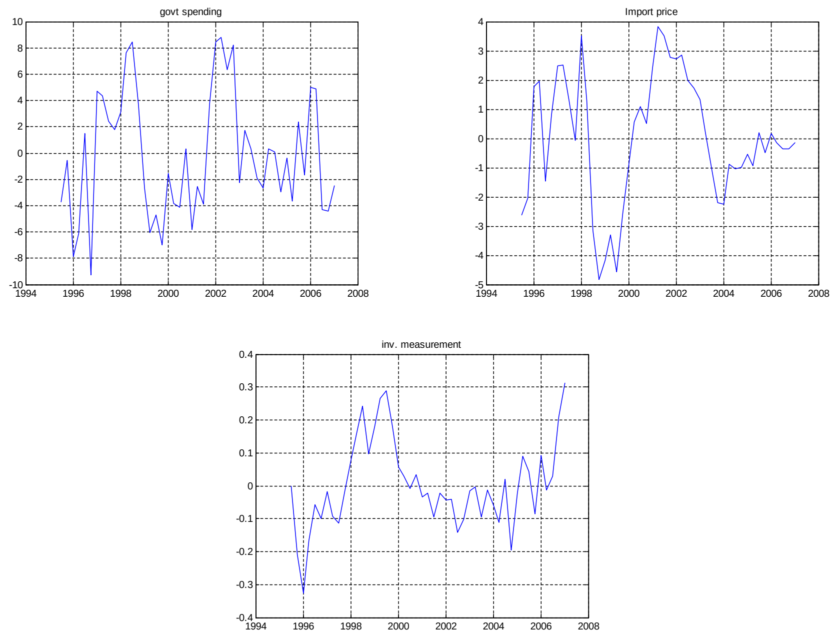
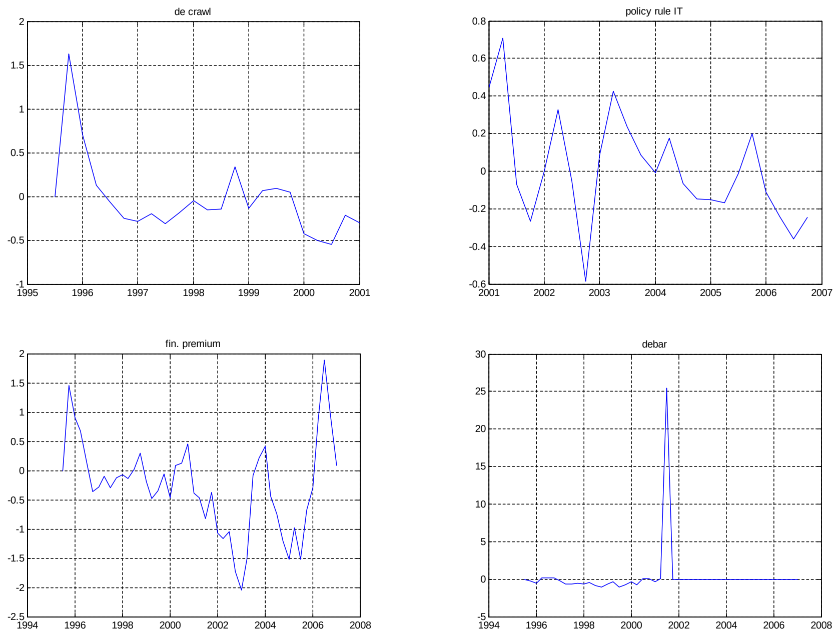


Figure 3.2 Deterministic part of nominal depreciation ($d\bar{e}_t$) rate of crawl, monetary-policy and financial-premium* shocks



*Calculated at mean parameter values

Figure 3.3 Other structural shocks*

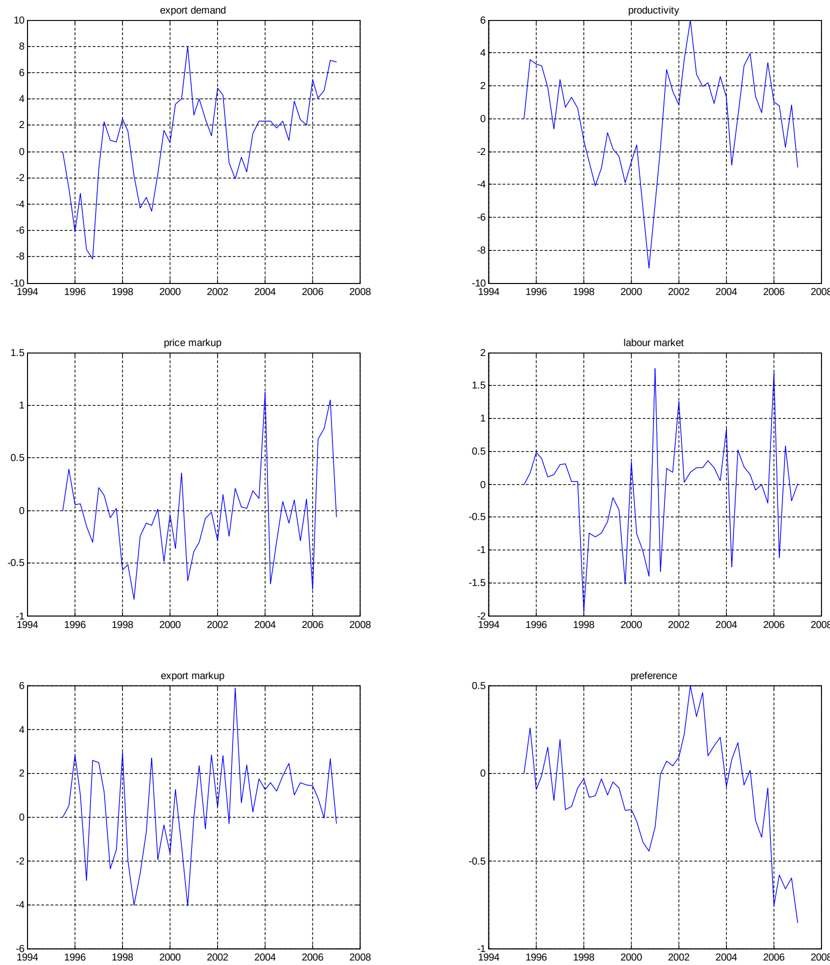
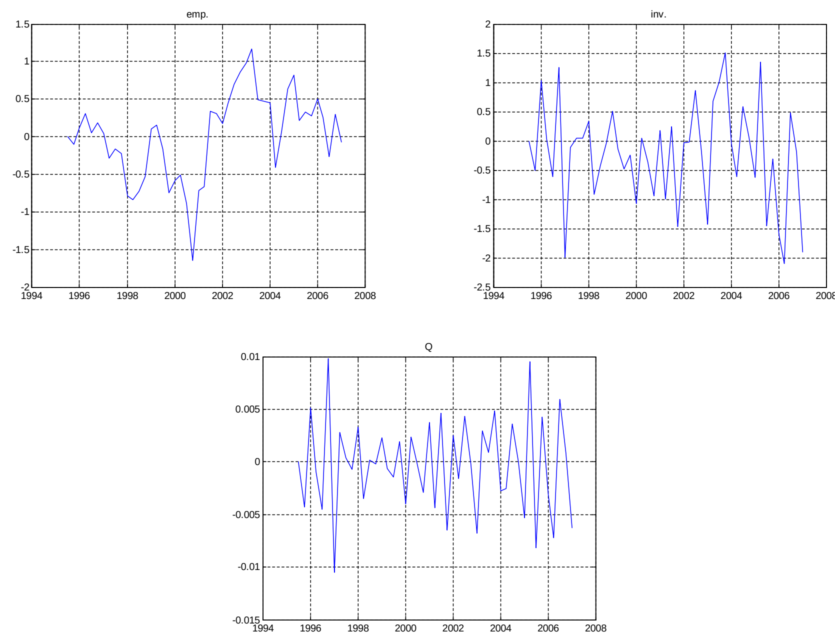


Figure 3.3 Other structural shocks (cont.)*

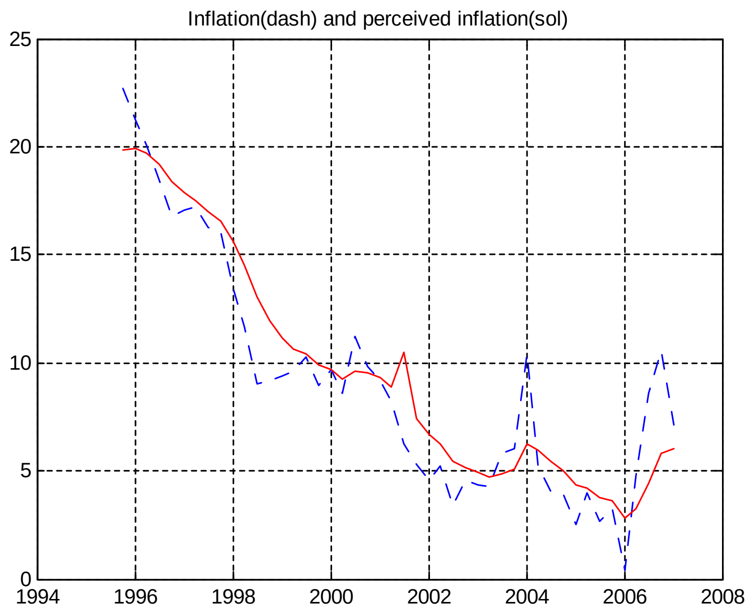


* Calculated at mean parameter values

An interesting feature of the model is that it contains an adaptive learning of agents about average inflation. Perception of average inflation is measured by $\bar{\pi}_t$. Agents gradually update their perception on inflation by taking into account the deviation of actual to perceived inflation. If inflation is higher than perceived, they partially increase their inflationary perception and *vica versa*. It is worth looking at the estimated evolution of this latent variable. It is worth noting, that long term inflation movement is filtered endogenously throughout the model estimation and has no exact connection with e.g. core inflation, though both are less volatile than actual inflation.

Figure 3.4 shows that the estimated perceived average inflation matches the long term disinflation in Hungary. This is, however, not very surprising. By construction, perceived average inflation is a '*filtered*' inflation. It is still worth comparing the two series to check its plausibility. The model predicts that in the first three-four years of the crawling-peg regime (until around late 1998-early 1999), inflation and its perception closely moved together. There was a significant drop in quarterly inflation from around 13 percent to around 7 percent. However, this was only gradually reflected in the estimated perceived average inflation. The model suggests that agents only *'beleived'* in the lower-inflation era with a considerable lag. During 2000 and 2001, *'perceived inflation'* stagnated. Thenafter, actual inflation was fuelled and perceived inflation also followed it with some lagged reaction. After the change in monetary policy regime, the relatively sudden drop in inflation was not fully perceived as permanent disinflation. The new regime needed a two-to-three years period to gain some credibility. The VAT increase in 2004 had only a temporary effect on inflation and on perceived inflation, as well. In contrast, the VAT and regulated price hikes in 2006 had some unpleasant consequences: perceived inflation also accelerated.

Figure 3.4 Perceived underlying inflation and actual inflation*



* Annualised quarter-on-quarter growth rates, calculated at mean parameter values. One should note that in this graph perceived trend inflation is defined as the one transformed back to be comparable to actual figures: perceived underlying inflation=$\bar{\pi}_t+\tilde{\chi}_t+E(\pi_t)$

3.5 Impulse response analysis

Impulse responses of the model to different structural shocks are displayed in *Figures 3.5–3.16*. Price and wage inflation, user cost, nominal and real interest rates are defined as annualized quarter-on-quarter growth rates. Impulse response functions are calculated at mean parameters estimated for the inflation targeting regime. Impulse responses are calculated as reactions of endogenous variables for a 1 percentage increase of innovation in the initial period. The exceptions are the two price markup shocks, labour market, policy rule and financial premium shocks where the initial increase is 0.25 percent.

To understand impulse responses, I briefly describe some distinctive features of the estimated model. First, agents in this model continously learn about average inflation. Consumer prices and wages are indexed to the *'perceived underlying inflation'*. Hence, due to gradual learning impulse responses of nominal wages and consumer prices are more persistent than that of the cyclical ones. The sluggish response of price and nominal wages implies relatively long lasting real wage response, as well. Due to the presence of non-optimizer consumers this also makes the response of consumption more persistent.

Second, the estimated adjustment cost of investments is higher than usually found in the literature (e.g. Smets and Wouters (2003)). This implies that the response of investments is slower and less volatile than in other DSGE models, and the it has usually the same magnitude as that of output or consumption.

Third, in most of the cases consumer prices are generally less responsive on impact and more persistent than nominal wages. This can be partly explained by the higher Calvo parameter of consumer prices than that of nominal wages.

As it is usual in New Keynesian models, a positive productivity shock decreases labor (hours). Consumption is higher in the long run, but in the short run this translates into lower consumption of non-optimizers.[44]

Monetary-policy shock has a negative effect on price and wage inflation. As mentioned above, part of the drop in inflation is devoted to the change in perceived average inflation, which induces agents to index to lower inflation. Indexation mechanisms amplify monetary policy shocks. In the case of financial premium shocks, GDP increases. This is mostly the result of growing consumption due to the presence of non-optimizers. Investments drop and export hardly change. The latter is the consequence of the relatively low price elasticity of exports.

Cost push shocks (consumer price markup and labour market shocks) have large impact on price and wage inflation. The two shocks result in different nominal and real interest rate paths. In the former case monetary policy tightens immediately, while in the in the latter case policy response is only gradual. Cost push shocks also accompany by significant real responses. In the case of labor market shock, the increase in non-optimizers income offset the reaction of optimizers and thus, total consumption is somewhat higher in the short run. Under both two shocks GDP, employment and investments drop. An interesting feature is that a foreign-import-price shock increases GDP which is a consequence of the large drop in imports due to relative price changes.

If a positive government spending shock occurs, one can observe that in the short run the increase in consumption of non-optimizers offset the decrease in optimizers consumption. Hence, the model replicates a (weakly) Keynesian multiplier effect in the short run. However, in the long run due to a crowding-out effect, investment activity has a negative effect on GDP which also feeds

[44]Nominal exchange rate appreciates even though there is a drop in interest rates in the short run. At a first glance this is difficult to explain. However, the short-run response of the nominal exchange rate depends on the sum of all future nominal-interest-rate changes. In other words, the nominal exchange rate is determined by forward-looking factors. However, the reaction of the nominal exchange rate might not be very important in this case, since according to variance decomposition the behavior of the nominal exchange rate is largely explained by non-productivity factors.

back into income of nonoptimizers and thus in the medium run the response of total consumption becomes negative.

Figure 3.5 Productivity shock

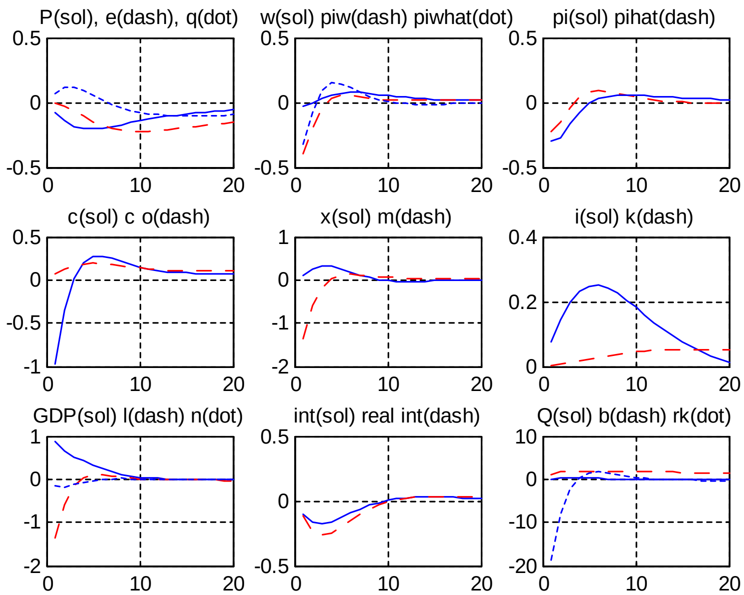


Figure 3.6 Gov't spending shock

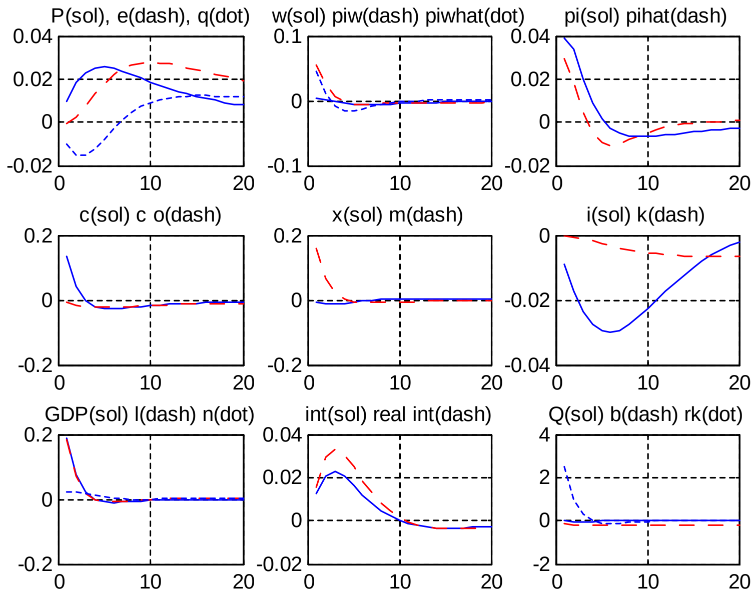


Figure 3.7 Monetary policy rule shock

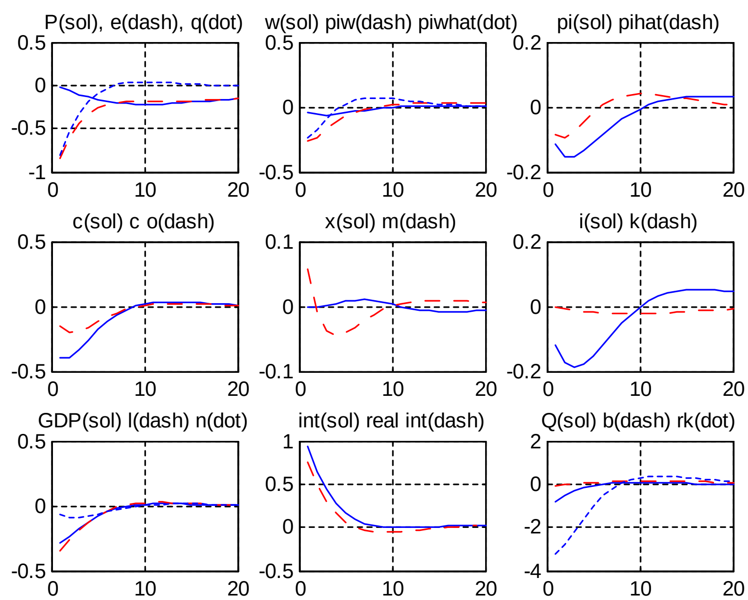


Figure 3.8 Financial premium shock

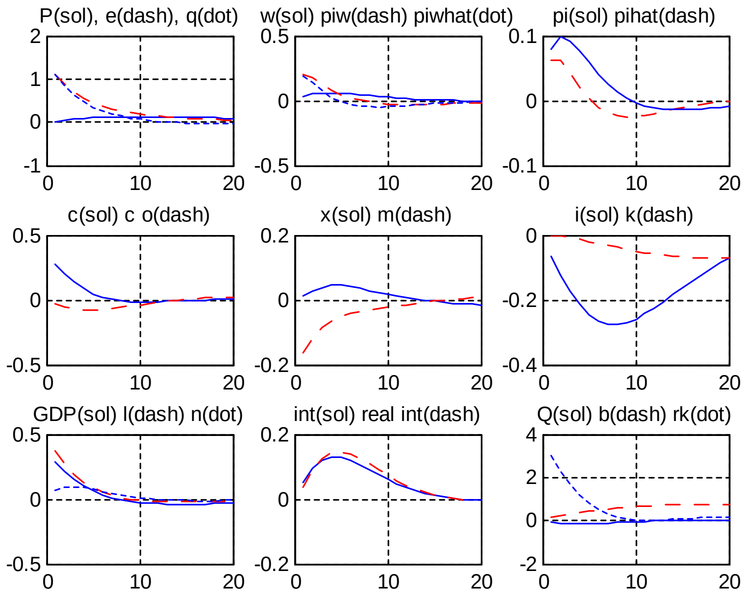


Figure 3.9 Consumer price markup shock

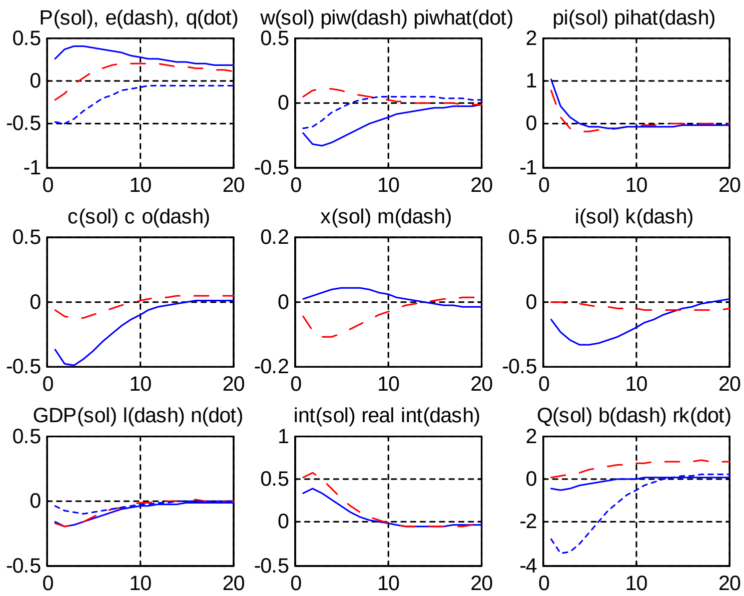


Figure 3.10 Export price markup shock

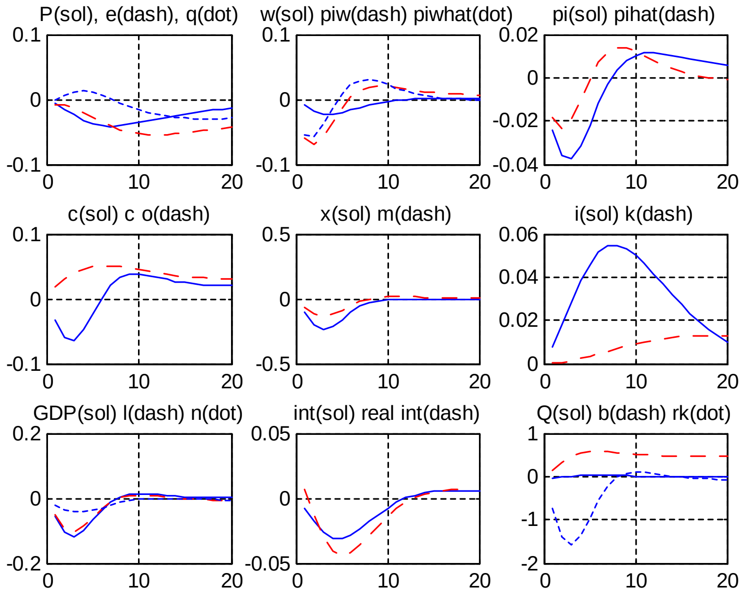


Figure 3.11 Labor market shock

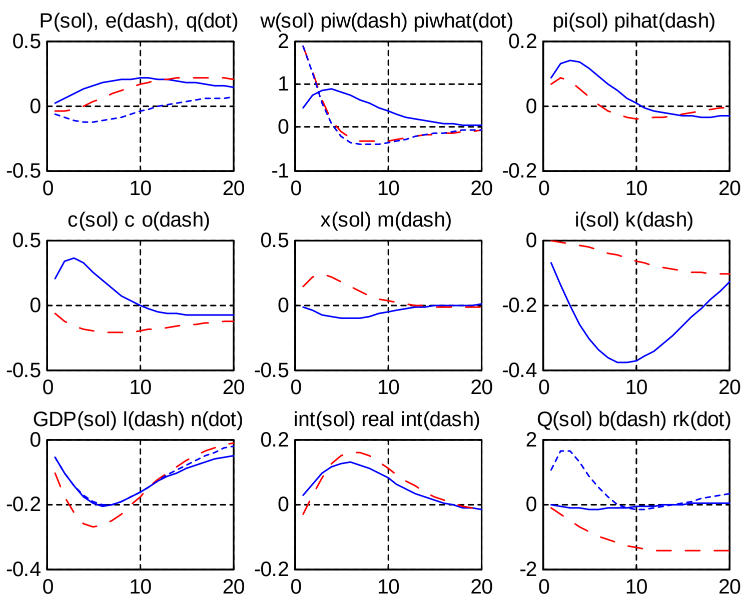


Figure 3.12 Preannounced nominal depreciation (crawl) shock

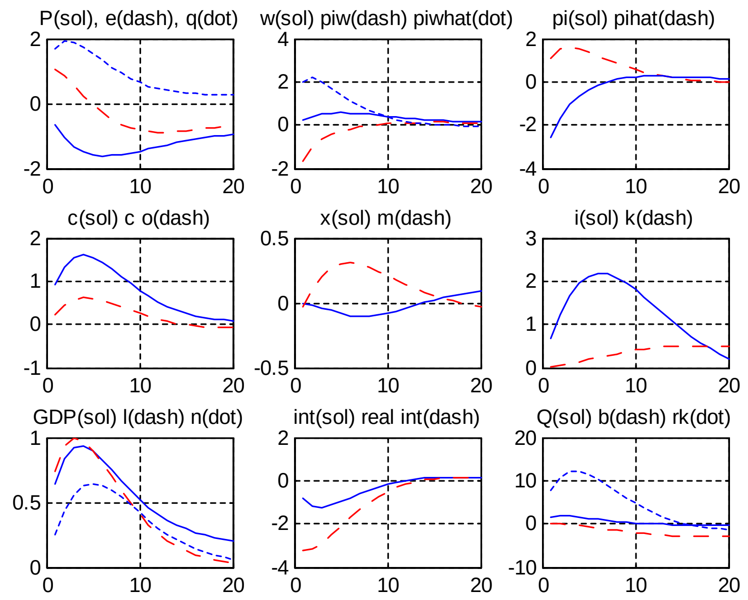


Figure 3.13 Import price shock

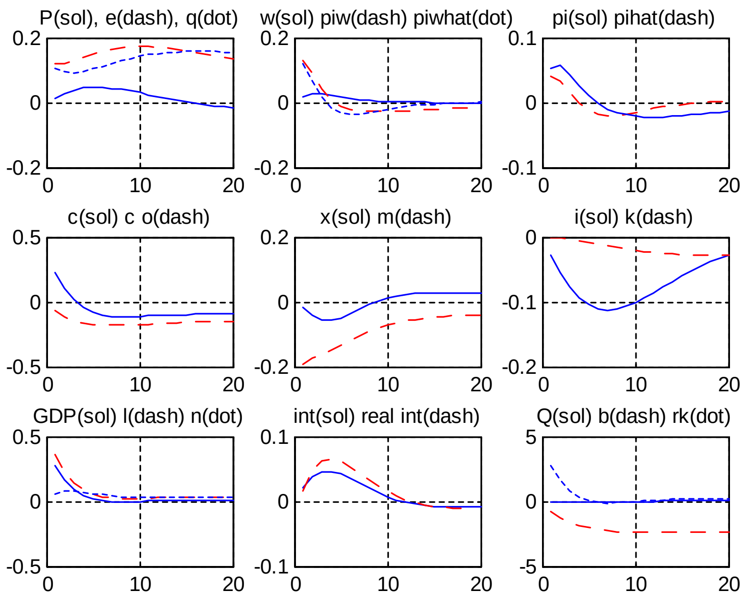


Figure 3.14 Export demand shock

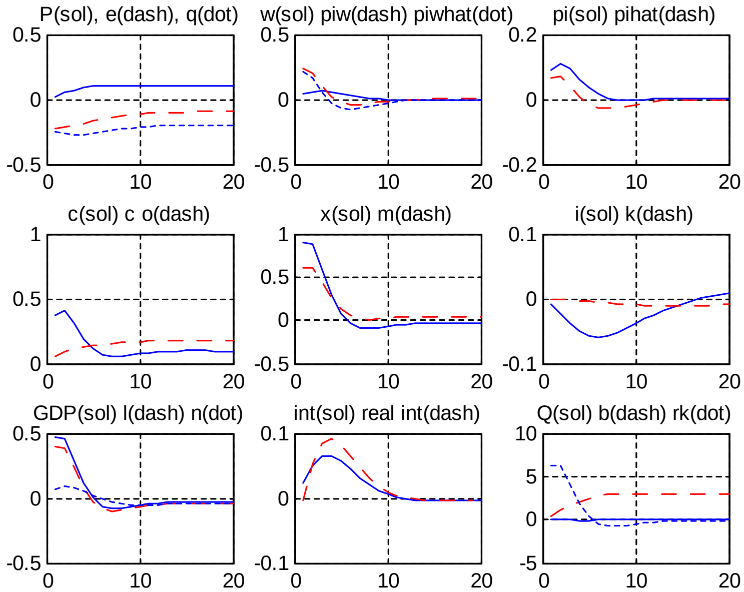


Figure 3.15 Investment shock

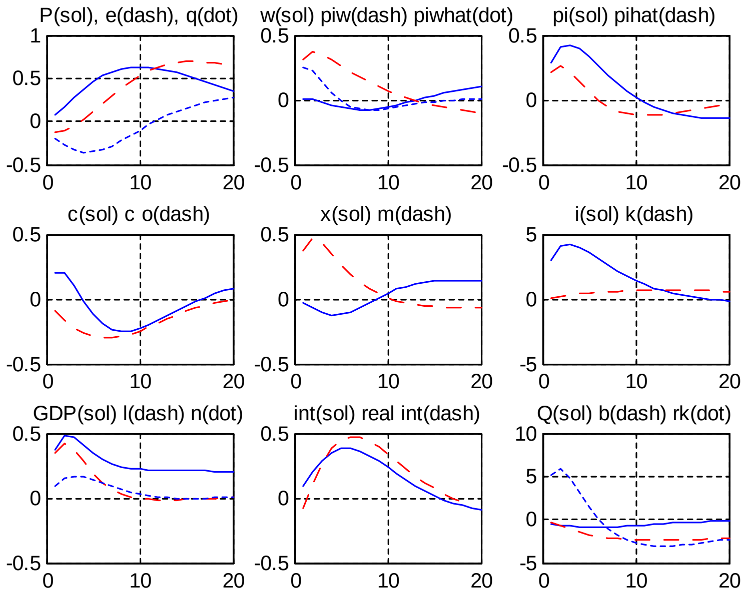
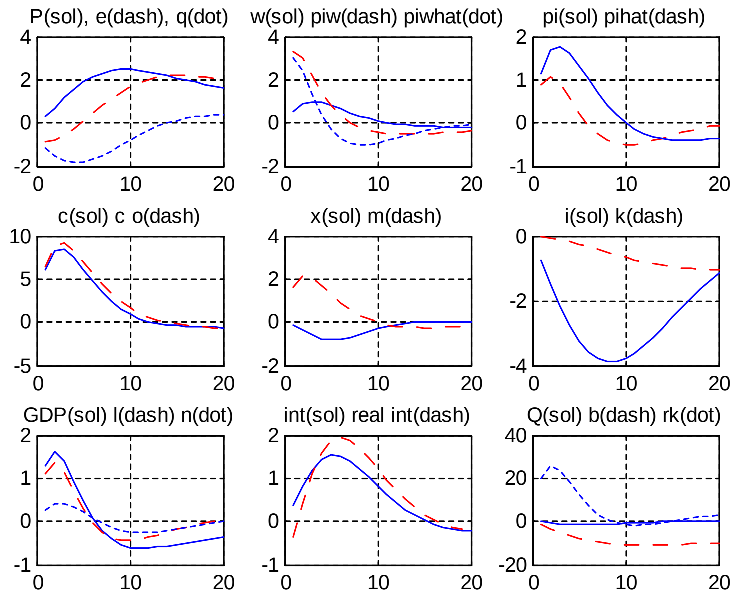


Figure 3.16 Consumption preference shock



3.6 Variance decomposition

Variance decomposition are calculated with parameters describing the inflation targeting regime. Therefore, it is not surprising that the trend depreciation shock (χ_t) does not influence forecast errors, as in this regime this observed shock is constantly kept zero. The results of the unconditional (long run) variance decomposition are summarized in *Table 3.7*, while forecast error variance decompositions are shown in *Tables 3.4–3.6*.

Consumer price inflation is affected in two channels: one through the perceived average inflation ($\bar{\pi}_t = -d\bar{q}_t$), and one through changes in cyclical inflation ($\tilde{\pi}_t$). An interesting feature that in the long run *'perceived underlying inflation'* is mostly explained by consumer price markup, labor market, productivity, investment and preference shocks. For example, Smets and Wouters (2003) and aAdolfson et al (2006) introduces an *'inflation target'* shock in order to capture disinflation of the 80's. According to Adolfson et al (2006) large part of the medium term variance of Sweden's inflation is explained by this shock. In contrast, in this model, there was no need to insert an additional shock to explain the disinflation process: a large part of long term variance of inflation can be explained by shocks other than markup shocks.[45]

[45] In the next section it is demonstrated that by handling disinflation by alternative models a larger part of unconditional variance of inflation is explained by either markup shocks or the shocks to the 'perceived underlying inflation'.

As shown before, consumer preference shocks are related to financial deepening or fiscal stimulus (through transfers). Inflationary perception is also affected by the changing pattern in consumption demand. The second factor of inflation, the cyclical one is also driven by the above shocks, though here, consumer price markup shocks plays more significant role and the labor market shock is less relevant. That is, consumer price markup shocks have more explanatory power for cyclical inflation, while labor market shocks have more influence on the long term inflationary perception of agents.

Cyclical nominal wages ($\hat{\pi}_t^w$) are governed by their own shocks both in the long and in the short run. This might indicate the model has rather limited ability to explain nominal wage fluctuations.This might serve as a motivation for further research by extending this model by a more detailed labor market setup.[46]

In the long run, the cyclical behaviour of real exchange rate is explained by financial premium, foreign import price, labor market, export demand and export price markup shocks. In the shorter run, however,real exchange rate movements are almost entirely driven by financial premium shocks. though consumer price markup and monetary policy rule shock gain some importance.

In the shorter run the nominal interest rate is explained by consumer price markup and monetary rule shocks. In addition, productivity, preference, financial premium and the labor market shock gain importance in determining monetary policy in the long run. Interestingly, financial premium shocks has only a limited effect on interest rates in the short run. That is, monetary policy tried to react to foreign interest rate fluctuations and changes in risk premium mostly on a longer horizon.

Real wages are governed by foreign shocks (foreign demand and export price markup shocks) showing that in a small, open economy, there is a close link between real wages in the export and in the domestic sector. Productivity shocks effects almost all real variables except for investments (consumption, imports, demand for labor and the rental rate of capital ($\tilde{r}_t^k$)). The export-demand shock ($\hat{x}_t^*$) is important in explaining the behavior of exports, import and labor demand of the export sector, real wages, but prices are isolated from this shock. Generally real variables are driven by productivity and export demand shocks. Not surprisingly, this result shows that in a small open economy, like Hungary, these are the prime determinants of output fluctuations. The overwhelming role of investment shock in investments and capital determination might show that the model is not very efficient in explaining investment behavior in Hungary.

In all horizons, financial premium and monetary shocks have only negligable effects on real variables except for the real exchange rate. They mostly influence the cyclical components of real and nominal exchange rate and the nominal interest rate. Real effects of financial premium and monetary-policy shock are only minor, which is in contrast with eurozone estimates of Smets and Wouters (2003). This conforms to Vonnák (2007) and Jakab et al (2006) that monetary

[46] Jakab and Kónya (2007) insert search and matching frictions into a simplified version of this model.

policy's effects in Hungary are rather limited on output.

The government consumption shock plays only a minor role in determining real variables in the short run, the only exception is the import demand of the domestic goods producing sector. In the longer run, imports and labor demand is only influenced in a limited extent by this shock. This might indicate that fiscal policy mostly affected the economy in indirect ways, through transfers, tax and regulated price changes etc., and not by direct purchases of goods and services.

Table 3.4 Forecast error variance decomposition $t = 1$ (one quarter)*

	$\tilde{g}_t$	$\widetilde{P}_t^{m*}$	$\tilde{\chi}_t$	$\tilde{x}_t^*$	$\widetilde{A}_t$	$\tilde{\upsilon}_t$	$\tilde{\upsilon}_t^w$	$\tilde{\upsilon}_t^x$	$\tilde{\varepsilon}_t^c$	$\tilde{\varepsilon}_t^{pr}$	$\tilde{\varepsilon}_t^r$	$\tilde{\varepsilon}_t^n$	$\tilde{\varepsilon}_t^I$	$\tilde{\varepsilon}_t^Q$	$\tilde{\varepsilon}_{kt}$
$\hat{\pi}$	0.7	0.2	0.0	0.7	8.2	85.0	0.9	0.6	1.1	0.6	0.2	0.0	1.8	0.0	0.0
$\hat{\pi}_t^x$	0.0	0.1	0.0	5.4	5.8	0.0	0.2	88.1	0.1	0.1	0.0	0.0	0.1	0.0	0.0
$\hat{\pi}_t^w$	0.1	0.1	0.0	0.4	0.8	0.2	96.7	0.4	0.6	0.4	0.1	0.0	0.1	0.0	0.0
$\bar{\pi}_t$ **	0.7	0.2	0.0	0.7	8.2	85.0	0.9	0.6	1.1	0.6	0.2	0.0	1.8	0.0	0.0
π_t^{***}	0.7	0.2	0.0	0.7	8.2	85.0	0.9	0.6	1.1	0.6	0.2	0.0	1.8	0.0	0.0
$\tilde{q}_t$	0.0	0.6	0.0	3.5	0.2	7.1	0.1	0.0	0.5	81.4	6.2	0.0	0.3	0.0	0.1
$\tilde{e}_t$	0.0	0.7	0.0	3.2	0.0	1.8	0.0	0.1	0.3	86.9	6.8	0.0	0.1	0.0	0.1
$d\tilde{e}_t$	0.0	0.7	0.0	3.2	0.0	1.8	0.0	0.1	0.3	86.9	6.8	0.0	0.1	0.0	0.1
$\hat{\imath}_t$	0.2	0.1	0.0	0.1	2.6	25.8	0.3	0.2	0.3	1.1	68.7	0.0	0.5	0.0	0.0
$\tilde{c}_t^{no}$	4.8	4.4	0.0	7.3	55.1	3.7	12.9	2.0	0.7	7.4	0.9	0.0	0.9	0.0	0.0
$\tilde{c}_t^o$	0.1	1.0	0.0	1.3	1.2	1.1	2.1	0.9	90.3	0.2	1.3	0.0	0.3	0.0	0.2
$\widetilde{w}_t$	0.0	0.1	0.0	0.2	0.1	5.6	93.1	0.3	0.3	0.2	0.0	0.0	0.0	0.0	0.0
$\tilde{x}_t$	0.0	0.0	0.0	83.4	1.0	0.0	0.0	15.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$\widetilde{m}_t^d$	11.6	3.6	0.0	4.3	68.3	0.0	2.0	0.2	2.2	4.6	0.1	0.0	3.2	0.0	0.0
$\widetilde{m}_t^x$	0.6	2.3	0.0	34.3	53.6	0.0	0.9	5.4	0.2	2.5	0.1	0.0	0.2	0.0	0.0
$\tilde{l}_t^d$	12.0	3.9	0.0	1.1	69.5	0.7	2.2	0.2	1.1	6.0	0.9	0.0	2.4	0.0	0.0
$\tilde{l}_t^x$	0.4	5.3	0.0	23.9	51.4	0.3	3.7	5.4	0.0	8.7	0.7	0.0	0.0	0.0	0.0
$\tilde{n}_t$	1.3	2.0	0.0	3.5	15.0	0.6	11.1	3.7	0.3	3.8	0.5	57.1	1.1	0.0	0.0
$\tilde{k}_t$	0.0	0.0	0.0	0.0	0.1	0.2	0.1	0.0	0.0	0.0	0.0	0.0	20.9	0.0	78.7
$\tilde{I}_t$	0.0	0.0	0.0	0.0	0.3	0.7	0.3	0.0	0.2	0.2	0.2	0.0	97.9	0.0	0.0
$\tilde{b}_t$	2.9	21.7	0.0	14.7	41.7	0.0	0.9	14.2	0.6	2.5	0.1	0.0	0.8	0.0	0.0
$\widetilde{Q}_t$	0.1	0.3	0.0	2.1	1.9	34.8	0.6	2.6	0.1	2.3	34.3	0.0	12.0	7.9	1.2
$\tilde{r}_t^k$	6.3	1.1	0.0	11.0	74.0	0.8	0.3	2.1	0.7	2.1	0.4	0.0	1.3	0.0	0.0
P_t^x	0.0	0.1	0.0	5.4	5.8	0.0	0.2	88.1	0.1	0.1	0.0	0.0	0.1	0.0	0.0

* Calculated at mean parameter values, **$d\bar{q}_t = -\bar{\pi}_t$ in IT

Table 3.5 Forecast error variance decomposition $t = 4$ (one year)*

	$\tilde{g}_t$	$\widetilde{P}_t^{m*}$	$\tilde{\chi}_t$	$\tilde{x}_t^*$	$\widetilde{A}_t$	$\tilde{\upsilon}_t$	$\tilde{\upsilon}_t^w$	$\tilde{\upsilon}_t^x$	$\tilde{\varepsilon}_t^c$	$\tilde{\varepsilon}_t^{pr}$	$\tilde{\varepsilon}_t^r$	$\tilde{\varepsilon}_t^n$	$\tilde{\varepsilon}_t^I$	$\tilde{\varepsilon}_t^Q$	$\tilde{\varepsilon}_{kt}$
$\hat{\pi}$	0.8	0.2	0.0	1.3	9.9	71.5	3.2	1.8	3.5	1.3	0.6	0.0	5.8	0.0	0.1
$\hat{\pi}_t^x$	0.0	0.1	0.0	9.0	6.2	0.0	0.5	83.6	0.1	0.2	0.0	0.0	0.1	0.0	0.0
$\hat{\pi}_t^w$	0.1	0.1	0.0	0.4	0.7	0.3	96.2	0.7	0.7	0.5	0.1	0.0	0.2	0.0	0.0
$\bar{\pi}_t$ **	1.0	0.3	0.0	2.1	13.5	57.7	4.8	2.9	5.5	2.1	0.9	0.0	9.0	0.0	0.1
π_t^{***}	0.8	0.2	0.0	1.3	9.9	71.5	3.2	1.8	3.5	1.3	0.6	0.0	5.8	0.0	0.1
$\tilde{q}_t$	0.1	0.9	0.0	6.7	0.8	11.0	0.5	0.0	1.4	72.8	4.4	0.0	1.2	0.0	0.3
$\tilde{e}_t$	0.0	1.4	0.0	5.0	0.2	1.2	0.0	0.3	0.3	85.4	5.7	0.0	0.1	0.0	0.2
$d\tilde{e}_t$	0.0	0.7	0.0	2.9	0.1	2.3	0.1	0.1	0.3	86.2	7.0	0.0	0.2	0.0	0.1
$\hat{\imath}_t$	0.6	0.4	0.0	0.8	8.5	34.1	2.9	1.9	3.1	4.9	37.4	0.0	5.3	0.0	0.0
$\tilde{c}_t^{no}$	1.8	2.7	0.0	6.2	21.3	6.8	44.4	8.0	1.2	5.7	0.7	0.0	1.1	0.0	0.0
$\tilde{c}_t^o$	0.2	2.0	0.0	2.1	2.5	1.8	4.4	1.9	82.4	0.5	1.0	0.0	0.8	0.0	0.4
$\widetilde{w}_t$	0.0	0.1	0.0	0.2	0.1	3.3	95.5	0.4	0.2	0.3	0.0	0.0	0.0	0.0	0.0
$\tilde{x}_t$	0.0	0.1	0.0	47.9	4.6	0.0	0.5	46.3	0.1	0.2	0.0	0.0	0.1	0.0	0.0
$\widetilde{m}_t^d$	7.4	5.0	0.0	7.5	46.0	0.5	10.1	1.8	7.0	5.4	0.1	0.0	9.3	0.0	0.0
$\widetilde{m}_t^x$	0.3	2.5	0.0	36.7	25.9	0.0	2.9	29.5	0.3	1.7	0.1	0.0	0.2	0.0	0.0
$\tilde{l}_t^d$	8.1	3.5	0.0	1.4	49.2	2.1	17.1	1.0	3.3	6.1	1.2	0.0	7.1	0.0	0.0
$\tilde{l}_t^x$	0.2	3.5	0.0	21.3	22.6	0.3	19.0	25.1	0.2	7.3	0.5	0.0	0.0	0.0	0.0
$\tilde{n}_t$	0.4	1.4	0.0	2.0	5.0	0.8	25.3	5.9	0.3	3.1	0.4	54.0	1.3	0.0	0.0
$\tilde{k}_t$	0.0	0.0	0.0	0.0	0.3	0.7	0.4	0.0	0.3	0.3	0.1	0.0	43.6	0.0	54.3
$\tilde{I}_t$	0.1	0.1	0.0	0.0	0.8	1.7	1.3	0.2	0.8	0.8	0.2	0.0	93.9	0.0	0.1
$\tilde{b}_t$	1.3	18.3	0.0	31.6	18.2	0.0	3.0	22.5	1.3	2.2	0.0	0.0	1.6	0.0	0.0
$\widetilde{Q}_t$	0.6	0.7	0.0	0.8	9.1	33.3	3.3	1.1	2.0	4.4	15.8	0.0	25.7	2.1	1.1
$\tilde{r}_t^k$	4.2	1.0	0.0	16.3	51.8	2.6	1.1	14.9	2.1	2.7	0.6	0.0	2.7	0.0	0.1
P_t^x	0.0	0.2	0.0	16.0	7.6	0.0	1.0	74.4	0.2	0.3	0.0	0.0	0.2	0.0	0.0

* Calculated at mean parameter values, **$d\bar{q}_t = -\bar{\pi}_t$ in IT

Table 3.6 Forecast error variance decomposition $t = 10$ (ten quarters)*

	$\tilde{g}_t$	$\widetilde{P}_t^{m*}$	$\tilde{\chi}_t$	$\tilde{x}_t^*$	$\widetilde{A}_t$	$\tilde{\upsilon}_t$	$\tilde{\upsilon}_t^w$	$\tilde{\upsilon}_t^x$	$\tilde{\varepsilon}_t^c$	$\tilde{\varepsilon}_t^{pr}$	$\tilde{\varepsilon}_t^r$	$\tilde{\varepsilon}_t^n$	$\tilde{\varepsilon}_t^I$	$\tilde{\varepsilon}_t^Q$	$\tilde{\varepsilon}_{kt}$
$\hat{\pi}$	0.9	0.3	0.0	1.3	11.4	68.8	3.3	2.4	3.7	1.3	0.6	0.0	5.9	0.0	0.1
$\hat{\pi}_t^x$	0.1	0.2	0.0	10.1	6.8	0.0	0.6	81.7	0.2	0.2	0.0	0.0	0.2	0.0	0.0
$\hat{\pi}_t^w$	0.1	0.1	0.0	0.5	0.8	0.3	95.8	0.9	0.7	0.5	0.1	0.0	0.2	0.0	0.0
$\bar{\pi}_t$ **	0.8	0.3	0.0	2.6	10.5	38.1	10.1	3.8	10.3	3.1	1.8	0.0	18.1	0.0	0.5
π_t^{***}	0.9	0.3	0.0	1.3	11.4	68.8	3.3	2.4	3.7	1.3	0.6	0.0	5.9	0.0	0.1
$\tilde{q}_t$	0.1	2.3	0.0	12.3	0.8	11.0	0.9	0.2	2.5	63.6	3.5	0.0	2.2	0.0	0.7
$\tilde{e}_t$	0.2	3.2	0.0	6.6	2.9	3.0	1.5	2.1	0.9	72.3	4.7	0.0	2.3	0.0	0.3
$d\tilde{e}_t$	0.0	0.7	0.0	2.8	0.3	2.5	0.3	0.2	0.5	85.3	6.9	0.0	0.5	0.0	0.1
$\hat{\imath}_t$	0.6	0.4	0.0	0.9	7.9	25.9	7.6	3.2	7.2	7.9	24.8	0.0	13.4	0.0	0.2
$\tilde{c}_t^{no}$	1.2	2.0	0.0	4.5	15.1	7.3	56.1	6.9	0.9	4.5	0.5	0.0	0.8	0.0	0.1
$\tilde{c}_t^o$	0.3	4.2	0.0	4.9	4.3	1.9	10.2	4.2	65.9	0.6	0.7	0.0	2.0	0.0	0.9
$\widetilde{w}_t$	0.0	0.1	0.0	0.1	0.2	2.8	95.8	0.4	0.2	0.3	0.0	0.0	0.0	0.0	0.1
$\tilde{x}_t$	0.0	0.2	0.0	41.2	5.7	0.0	1.9	49.9	0.4	0.4	0.0	0.0	0.2	0.0	0.1
$\widetilde{m}_t^d$	6.2	6.3	0.0	7.6	39.4	1.4	13.3	2.0	7.6	5.5	0.1	0.0	10.5	0.0	0.1
$\widetilde{m}_t^x$	0.2	2.8	0.0	33.4	23.9	0.0	3.9	33.6	0.3	1.5	0.1	0.0	0.2	0.0	0.0
$\tilde{l}_t^d$	6.1	2.7	0.0	1.2	37.2	2.4	34.3	1.1	2.8	4.6	1.0	0.0	6.6	0.0	0.0
$\tilde{l}_t^x$	0.1	2.9	0.0	16.9	16.9	0.2	33.1	22.8	0.5	6.0	0.4	0.0	0.2	0.0	0.0
$\tilde{n}_t$	0.2	1.0	0.0	1.2	2.3	0.8	42.8	4.1	0.2	2.0	0.2	44.3	1.0	0.0	0.0
$\tilde{k}_t$	0.1	0.1	0.0	0.0	1.0	1.8	2.1	0.3	1.3	1.1	0.1	0.0	58.7	0.0	33.4
$\tilde{I}_t$	0.1	0.3	0.0	0.0	1.7	3.0	4.7	0.7	3.0	2.2	0.2	0.0	83.6	0.0	0.4
$\tilde{b}_t$	0.7	17.7	0.0	40.0	10.5	0.2	7.1	16.3	2.1	2.6	0.0	0.0	2.8	0.0	0.0
$\widetilde{Q}_t$	0.4	0.6	0.0	0.6	7.1	20.8	6.1	2.0	4.2	4.5	8.6	0.0	43.1	1.1	0.8
$\tilde{r}_t^k$	4.0	0.9	0.0	15.4	49.0	3.6	1.1	16.8	2.3	2.7	0.6	0.0	3.1	0.0	0.6
P_t^x	0.0	0.2	0.0	22.4	7.3	0.0	2.2	66.5	0.4	0.4	0.0	0.0	0.2	0.0	0.2

* Calculated at mean parameter values, $^{**}d\bar{q}_t = -\bar{\pi}_t$ in IT

Table 3.7 Unconditional variance decomposition*

	$\tilde{g}_t$	$\widetilde{P}_t^{m*}$	$\tilde{\chi}_t$	$\tilde{x}_t^*$	$\widetilde{A}_t$	$\tilde{\upsilon}_t$	$\tilde{\upsilon}_t^w$	$\tilde{\upsilon}_t^x$	$\tilde{\varepsilon}_t^c$	$\tilde{\varepsilon}_t^{pr}$	$\tilde{\varepsilon}_t^r$	$\tilde{\varepsilon}_t^n$	$\tilde{\varepsilon}_t^I$	$\tilde{\varepsilon}_t^Q$	$\tilde{\varepsilon}_{kt}$
$\hat{\pi}$	0.8	0.4	0.0	1.3	11.0	65.2	4.1	2.6	4.4	1.4	0.7	0.0	8.0	0.0	0.1
$\hat{\pi}_t^x$	0.1	0.2	0.0	10.2	6.8	0.0	0.6	81.6	0.2	0.2	0.0	0.0	0.2	0.0	0.0
$\hat{\pi}_t^w$	0.1	0.1	0.0	0.5	0.7	0.3	95.8	0.9	0.8	0.5	0.1	0.0	0.2	0.0	0.0
$\bar{\pi}_t$ **	0.7	0.8	0.0	2.4	10.0	32.2	10.5	4.1	9.9	2.6	1.8	0.0	23.6	0.0	1.3
π_t^{***}	0.8	0.4	0.0	1.3	11.0	65.2	4.1	2.6	4.4	1.4	0.7	0.0	8.0	0.0	0.1
$\tilde{q}_t$	0.3	12.9	0.0	30.8	4.4	4.2	9.1	6.5	2.4	23.8	1.2	0.0	3.8	0.0	0.8
$\tilde{e}_t$	0.4	5.6	0.0	7.3	6.4	4.5	13.7	5.8	6.5	33.3	2.7	0.0	11.9	0.0	1.9
$d\tilde{e}_t$	0.0	0.7	0.0	2.8	0.3	2.5	0.3	0.2	0.5	84.9	6.8	0.0	0.8	0.0	0.2
$\hat{\imath}_t$	0.5	0.6	0.0	1.4	7.5	24.3	7.9	3.1	7.1	7.7	22.5	0.0	16.6	0.0	0.8
$\tilde{c}_t^{no}$	1.1	3.2	0.0	7.6	13.6	6.8	52.3	6.7	1.0	4.5	0.5	0.0	2.2	0.0	0.6
$\tilde{c}_t^o$	0.4	13.1	0.0	24.6	6.3	0.7	17.7	8.4	24.3	1.6	0.2	0.0	1.0	0.0	1.6
$\widetilde{w}_t$	0.0	0.3	0.0	0.6	0.2	2.8	93.3	0.5	0.2	0.4	0.0	0.0	1.0	0.0	0.5
$\tilde{x}_t$	0.1	1.2	0.0	40.7	5.6	0.1	2.5	46.7	0.5	0.7	0.0	0.0	1.5	0.0	0.3
$\widetilde{m}_t^d$	4.3	10.4	0.0	17.9	28.4	1.2	13.6	4.9	6.1	4.9	0.1	0.0	8.1	0.0	0.3
$\widetilde{m}_t^x$	0.2	3.1	0.0	33.4	23.6	0.0	4.1	33.3	0.3	1.6	0.1	0.0	0.2	0.0	0.0
$\tilde{l}_t^d$	5.7	2.5	0.0	1.2	34.9	2.3	37.5	1.2	2.8	4.5	0.9	0.0	6.4	0.0	0.1
$\tilde{l}_t^x$	0.2	5.8	0.0	21.0	14.8	0.3	30.7	20.0	1.0	5.4	0.3	0.0	0.5	0.0	0.1
$\tilde{n}_t$	0.2	2.8	0.0	5.3	2.6	0.7	43.8	4.3	0.6	1.9	0.2	36.7	0.8	0.0	0.1
$\tilde{k}_t$	0.1	0.6	0.0	0.2	2.1	2.9	11.2	1.2	6.1	3.8	0.1	0.0	54.5	0.0	17.3
$\tilde{I}_t$	0.1	0.3	0.0	0.1	1.9	3.2	7.9	1.0	4.7	3.1	0.2	0.0	76.4	0.0	1.1
$\tilde{b}_t$	0.5	18.3	0.0	38.6	7.1	0.4	15.9	10.7	3.2	3.5	0.0	0.0	1.3	0.0	0.5
$\widetilde{Q}_t$	0.4	0.6	0.0	0.5	6.3	18.4	6.0	1.9	4.1	4.2	7.6	0.0	48.3	1.0	0.7
$\tilde{r}_t^k$	3.6	1.3	0.0	14.8	45.1	3.4	2.3	15.7	2.5	2.6	0.6	0.0	6.7	0.0	1.3
P_t^x	0.1	1.3	0.0	23.3	7.1	0.1	2.7	62.1	0.5	0.8	0.0	0.0	1.6	0.0	0.3

* Calculated at mean parameter values, **$d\bar{q}_t = -\bar{\pi}_t$ in IT

3.7 An alternative model without real time adaptive learning

Disinflation was endogenously detemined by an adaptive learning mechanism in the model outlined above (henceforth called *Baseline Model*) In the *baseline model* the underlying component of inflation was made endogenous by introducing an adaptive learning scheme.

It should be emphasised that the solution in the *baseline model* does not assume non-rationality: agents take into account that inflation has a permanent component (on top of the exogenously set rate of currency depreciation in the crawling peg regime) and all agents fully index their prices and wages to it first. Optimizing agents set their prices and wages to the optimal level, so this is simply a convenient way of writing Phillips-curves.

As mentioned before, this solution enabled us to explain long term variance of inflation without adding an extra shock. A natural question arises: what are the consequences of choosing this type of 'filtering'. One can suspect that inserting the adaptive learning of '*perceived underlying inflation*' would have created an '*intrinsic*' inertia in both price and wage setting and indexation parameters are estimated to be low. For this purpose, I estimated an alternative model which filters inflation in a different way. The '*intrinsic*' inertia in price and wage setting was switched off and an '*extrinsic*' shock was introduced .

As an alternative model, I experimented with estimating the model by estimating the shock of *'perceived underlying inflation'* with Bayesian methods. For this, raw inflation data were simply demeaned after substracting the exogenous rate of crawl. Then, equation (159) was switched off and a simple equation determining the change in '*underlying*' inflation (see equation (184)) was used. This way, the model was estimated on the same data set as the *Baseline Model.*

$$d\bar{q}_t = \tilde{\chi}_t, \tag{184}$$

As mentioned before, in *the alternative model* the shocks to the *'perceived underlying inflation'* was estimated and the learning rule was switched off. Apart from this, the model has the same properties as the baseline model. *The alternative model* was then estimated by Bayesian method with exactly the same prior distributions and number of draws that of the *Baseline Model*. The only exception is that the gain parameter (g) was set to zero and that the standard error of the 'perceived underlying inflation' shock was given a prior of Inverse Gamma distribution with mean 0.5 and degrees of freedom of 2. *Table 3.8* and *3.9* show the estimation results of the alternative model.

Almost all estimated structural parameters in *the alternative model* were found to be very close to that in the *Baseline Model*. The only slight difference is a lower degree of indexation in consumer prices for the inflation targeting regime. Hence, one can conclude that the role of *intrinsic'* inertia in the *Baseline Model* was not generated by the way of how 'perceived underlying' inflation is formed.

Table 3.8 Estimated parameters of shocks in the alternative model

		Prior distribution			Baseline model			Alternative model		
					Estimated posterior		90%	Estimated posterior		90%
		Type	Mean	Stand. err.	Mode	Mean	prob. int.	Mode	Mean	prob. int.
Standard errors										
productivity	σ_A	I.Gam.	0.5	2*	2.080	2.152	$[1.82, 2.55]$	2.037	2.110	$[1.78, 2.51]$
export demand	σ_x	I.Gam.	0.5	2*	2.352	2.464	$[2.06, 2.95]$	2.345	2.456	$[2.07, 2.92]$
cons. pref.	σ_c	I.Gam.	0.5	2*	0.146	0.203	$[0.11, 0.33]$	0.151	0.213	$[0.12, 0.33]$
cons. price markup	σ_p	I.Gam.	0.5	2*	0.397	0.420	$[0.34, 0.52]$	0.351	0.380	$[0.28, 0.50]$
export price markup	σ_{px}	I.Gam.	0.5	2*	1.873	2.182	$[1.64, 2.87]$	1.862	2.198	$[1.66, 2.92]$
labor market	σ_w^{cr}	I.Gam.	0.5	2*	0.824	0.922	$[0.65, 1.26]$	0.755	0.862	$[0.59, 1.21]$
labor market	σ_w^{it}	I.Gam.	0.5	2*	0.609	0.932	$[0.54, 1.42]$	0.662	1.016	$[0.58, 1.57]$
investments	σ_I	I.Gam.	0.5	2*	0.969	1.003	$[0.76, 1.27]$	0.945	0.979	$[0.74, 1.24]$
Equity premium	σ_Q	I.Gam.	0.5	2*	0.167	0.393	$[0.11, 0.99]$	0.167	0.393	$[0.10, 1.30]$
policy rule	σ_r^{cr}	I.Gam.	0.5	2*	0.574	0.602	$[0.48, 0.76]$	0.573	0.601	$[0.48, 0.76]$
policy rule	σ_r^{it}	I.Gam.	0.5	2*	0.229	0.247	$[0.19, 0.32]$	0.190	0.210	$[0.13, 0.30]$
fin. premium	σ_{pr}^{cr}	I.Gam.	0.5	2*	0.221	0.372	$[0.17, 0.67]$	0.237	0.366	$[0.17, 0.65]$
fin. premium	σ_{pr}^{it}	I.Gam.	0.5	2*	0.486	0.666	$[0.36, 1.06]$	0.340	0.506	$[0.27, 0.85]$
employment	σ_n	I.Gam.	0.5	2*	0.369	0.383	$[0.30, 0.49]$	0.341	0.357	$[0.27, 0.46]$
perceived average inflation	σ_χ	I.Gam.	0.5	2*		Fixed at 0.12		0.415	0.456	$[0.29, 0.67]$
Autoregressive coefficients										
productivity	ρ_A	Beta	0.8	0.1	0.577	0.552	$[0.43, 0.68]$	0.530	0.507	$[0.38, 0.63]$
export demand	ρ_x	Beta	0.8	0.1	0.616	0.625	$[0.51, 0.73]$	0.617	0.621	$[0.50, 0.73]$
cons. pref.	ρ_c	Beta	0.8	0.1	0.833	0.767	$[0.60, 0.88]$	0.830	0.758	$[0.60, 0.88]$
labor market	ρ_w^{cr}	Beta	0.8	0.1	0.486	0.480	$[0.32, 0.64]$	0.501	0.498	$[0.33, 0.66]$
labor market	ρ_w^{it}	Beta	0.8	0.1	0.797	0.661	$[0.43, 0.87]$	0.779	0.656	$[0.44, 0.86]$
export markup	ρ_x	Beta	0.5	0.15	0.317	0.318	$[0.15, 0.50]$	0.308	0.308	$[0.15, 0.49]$
investments	ρ_I	Beta	0.8	0.1	0.497	0.488	$[0.33, 0.65]$	0.490	0.484	$[0.33, 0.65]$
fin. premium	ρ_{pr}^{cr}	Beta	0.8	0.1	0.899	0.833	$[0.69, 0.93]$	0.895	0.837	$[0.71, 0.93]$
fin. premium	ρ_{pr}^{it}	Beta	0.8	0.1	0.872	0.820	$[0.70, 0.92]$	0.907	0.853	$[0.75, 0.94]$
employment	ρ_n	Beta	0.8	0.1	0.790	0.770	$[0.64, 0.89]$	0.824	0.796	$[0.67, 0.91]$
perceived average inflation	σ_χ		Fixed			0.53			0	

Table 3.9 Estimated structural parameters in the alternative model

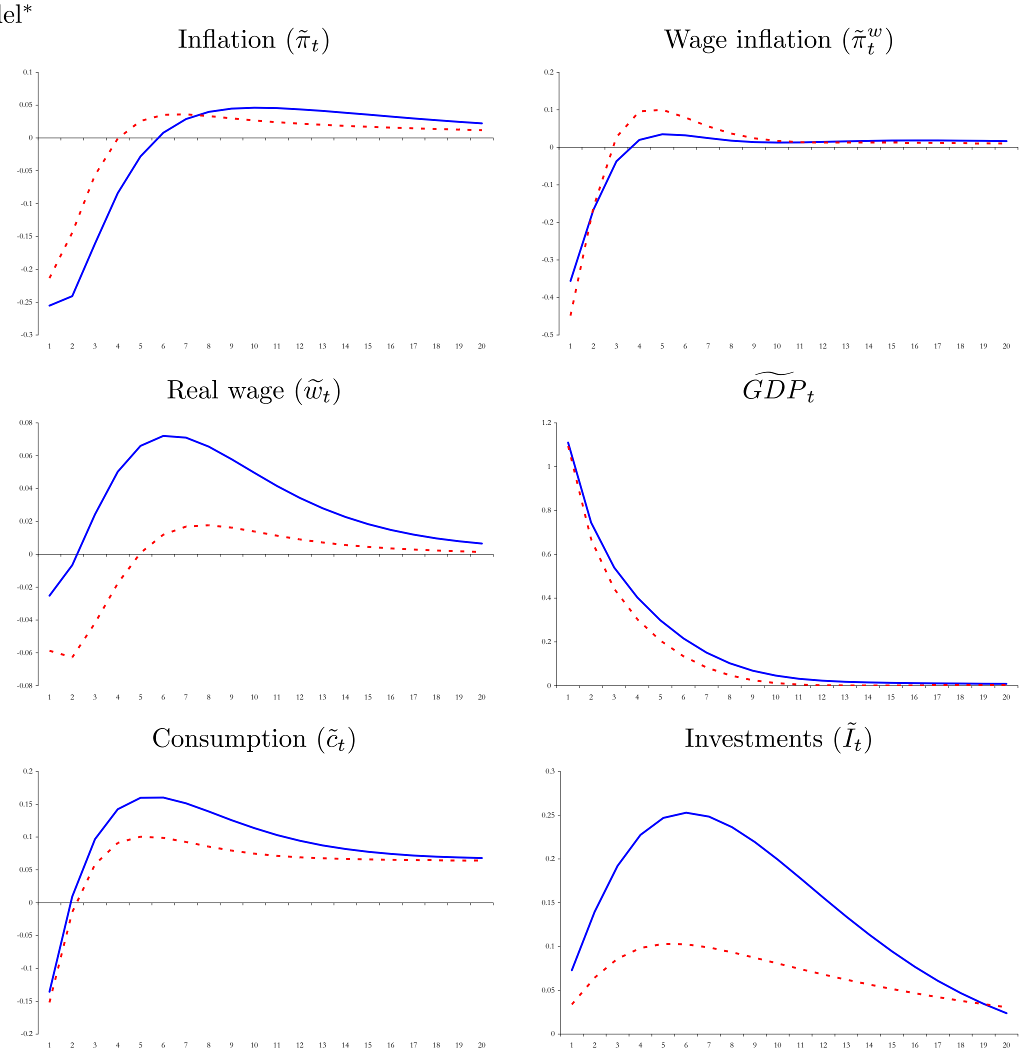
		Prior distribution			Baseline model			Alternative model		
					Estimated posterior		90%	Estimated posterior		90%
		Type	Mean	Stand. err.	Mode	Mean	prob. int.	Mode	Mean	prob. int.
Utility function parameters										
consumption	σ	Norm.	2.00	0.40	1.680	1.814	[1.18, 2.46]	1.812	1.807	[1.16, 2.47]
habit	h	Beta	0.75	0.15	0.597	0.646	[0.45, 0.83]	0.546	0.619	[0.42, 0.81]
Price and wage setting param.										
ind. cons. prices	ϑ_p^{cr}	Beta	0.60	0.20	0.873	0.821	[0.63, 0.96]	0.783	0.756	[0.52, 0.94]
ind. cons. prices	ϑ_p^{it}	Beta	0.60	0.20	0.416	0.431	[0.22, 0.66]	0.280	0.328	[0.13, 0.56]
ind. exp. prices	ϑ_x^{cr}	Beta	0.60	0.20	0.215	0.290	[0.10, 0.55]	0.201	0.281	[0.10, 0.53]
ind. exp. prices	ϑ_x^{it}	Beta	0.60	0.20	0.383	0.494	[0.18, 0.83]	0.380	0.481	[0.18, 0.82]
ind. wages	ϑ_w^{cr}	Beta	0.60	0.20	0.112	0.169	[0.05, 0.34]	0.105	0.166	[0.05, 0.34]
ind. wages	ϑ_w^{it}	Beta	0.60	0.20	0.107	0.185	[0.05,0.40]	0.121	0.211	[0.06, 0.44]
Calvo cons. prices	γ_p^{cr}	Beta	0.50	0.20	0.939	0.938	[0.92, 0.96]	0.924	0.918	[0.89, 0.94]
Calvo cons. prices	γ_p^{it}	Beta	0.50	0.20	0.929	0.921	[0.88, 0.95]	0.932	0.922	[0.88, 0.96]
Calvo exp. prices	γ_x^{cr}	Beta	0.50	0.20	0.850	0.824	[0.75, 0.89]	0.851	0.823	[0.74, 0.90]
Calvo exp. prices	γ_x^{it}	Beta	0.50	0.20	0.827	0.810	[0.73, 0.89]	0.829	0.808	[0.73, 0.89]
Calvo wages	γ_w^{cr}	Beta	0.50	0.20	0.714	0.698	[0.58, 0.81]	0.690	0.662	[0.55, 0.77]
Calvo wages	γ_w^{it}	Beta	0.50	0.20	0.711	0.657	[0.46, 0.88]	0.679	0.617	[0.44, 0.81]
Other parameters										
exp. elasticity	θ_x	Beta	0.50	0.10	0.510	0.534	[0.40, 0.67]	0.504	0.530	[0.40, 0.67]
exp. smooth.	h_x	Beta	0.75	0.15	0.503	0.507	[0.35, 0.66]	0.486	0.492	[0.34, 0.64]
ir. smooth.	ζ_i	U(0,1)	0.50	0.29	0.766	0.761	[0.67, 0.84]	0.675	0.679	[0.53, 0.80]
policy rule	ζ_π	Norm.	1.50	0.16	1.375	1.379	[1.12, 1.65]	1.417	1.394	[1.14, 1.65]
gain	g	Beta	0.167	0.03	0.229	0.234	[0.17, 0.30]		fixed at 0	

3.7.1 A comparative impulse response analysis

A comparative impulse response analysis between the *alternative* and the *baseline* model is also performed with the same setting of shocks as described before (see *Figure 3.17 - 3.21*). Generally, most of the impulse response functions are close to each other. One can observe slight differences in nominal wage reactions: in the *alternative* model wages are somewhat more flexible. Moreover, consumer prices in the *alternative* model generally respond to a lesser extent. This can be explained by two factors. First, the degree of price indexation is somewhat higher in the *alternative* model. Therefore, prices move less in the short run as inflation changes only gradually. The second factor lies exactly on the learning properties of *'perceived underlying inflation'*. While in the *baseline* model, *'perceived underlying inflation'* is also modified for a prolonged period of time, it does not change in the *alternative* model. Therefore, the *alternative* model generally features a more modest reaction in prices. In turn, this also modifies the evolution of real wages.

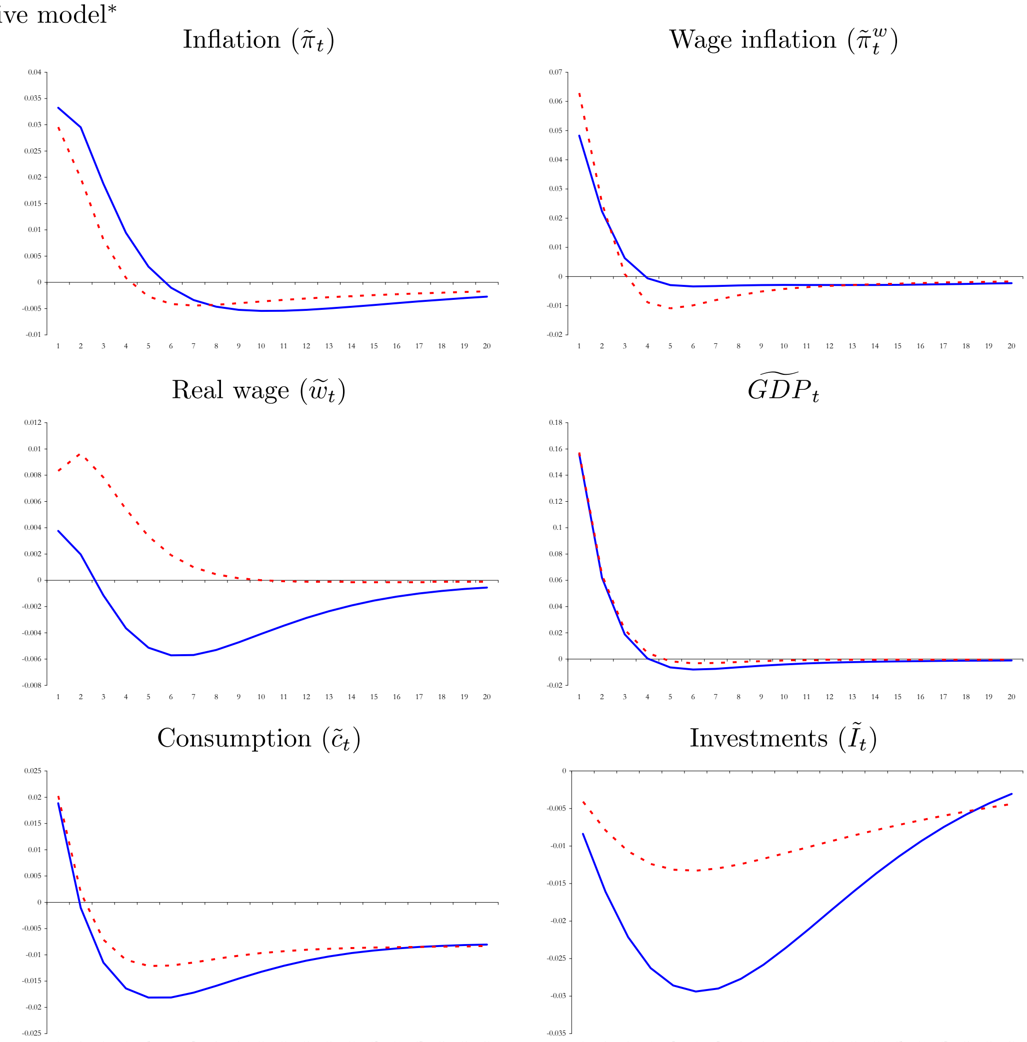
A monetary policy rule shock leads to a weaker drop in inflation in the *alternative* model. The evolution of real wages are markedly different under productivity, government spending shocks. It can also be observed that investments respond to a smaller extent in the *alternative* than in the *baseline model.*

Figure 3.17 Productivity shock in the baseline model and in the alternative model*



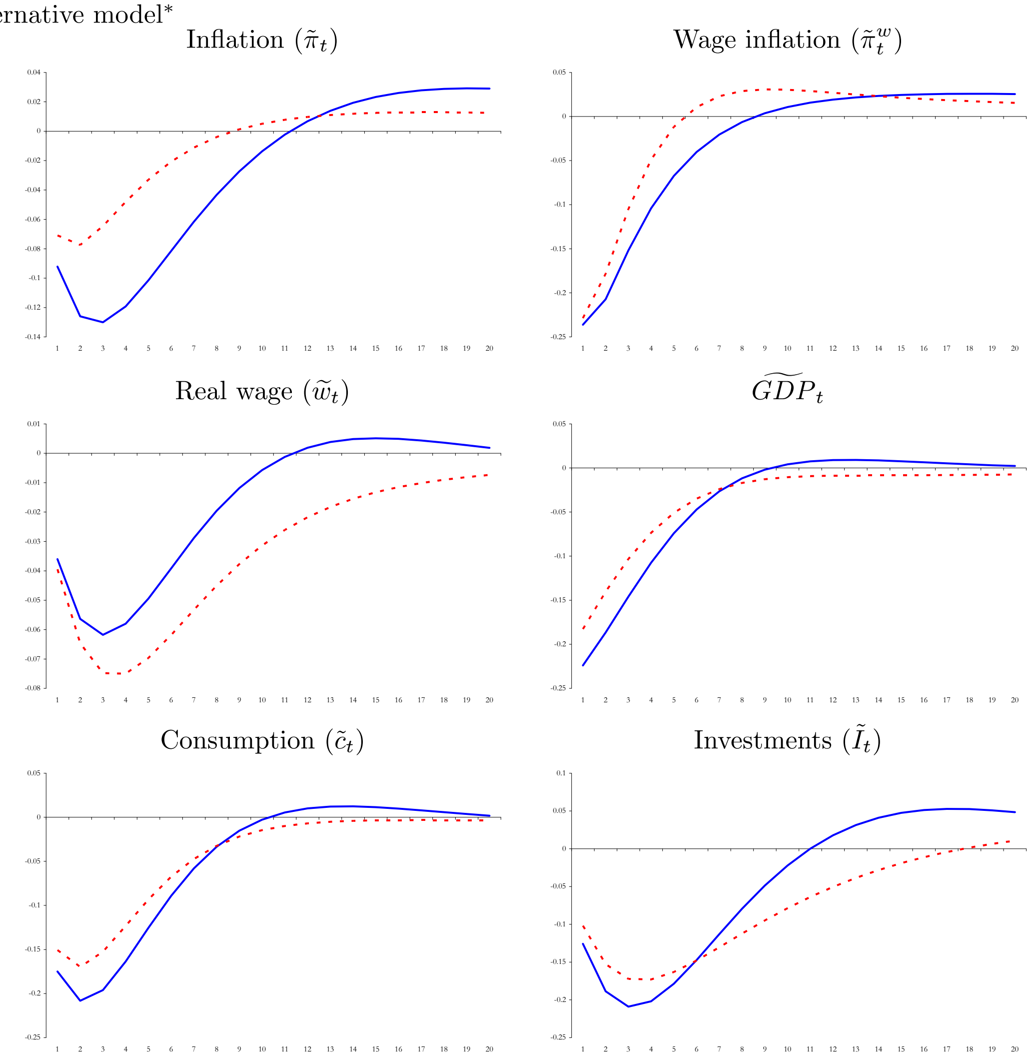
* solid: baseline model, dashed: alternative model

Figure 3.18 Gov't spending shock in the baseline model and in the alternative model*



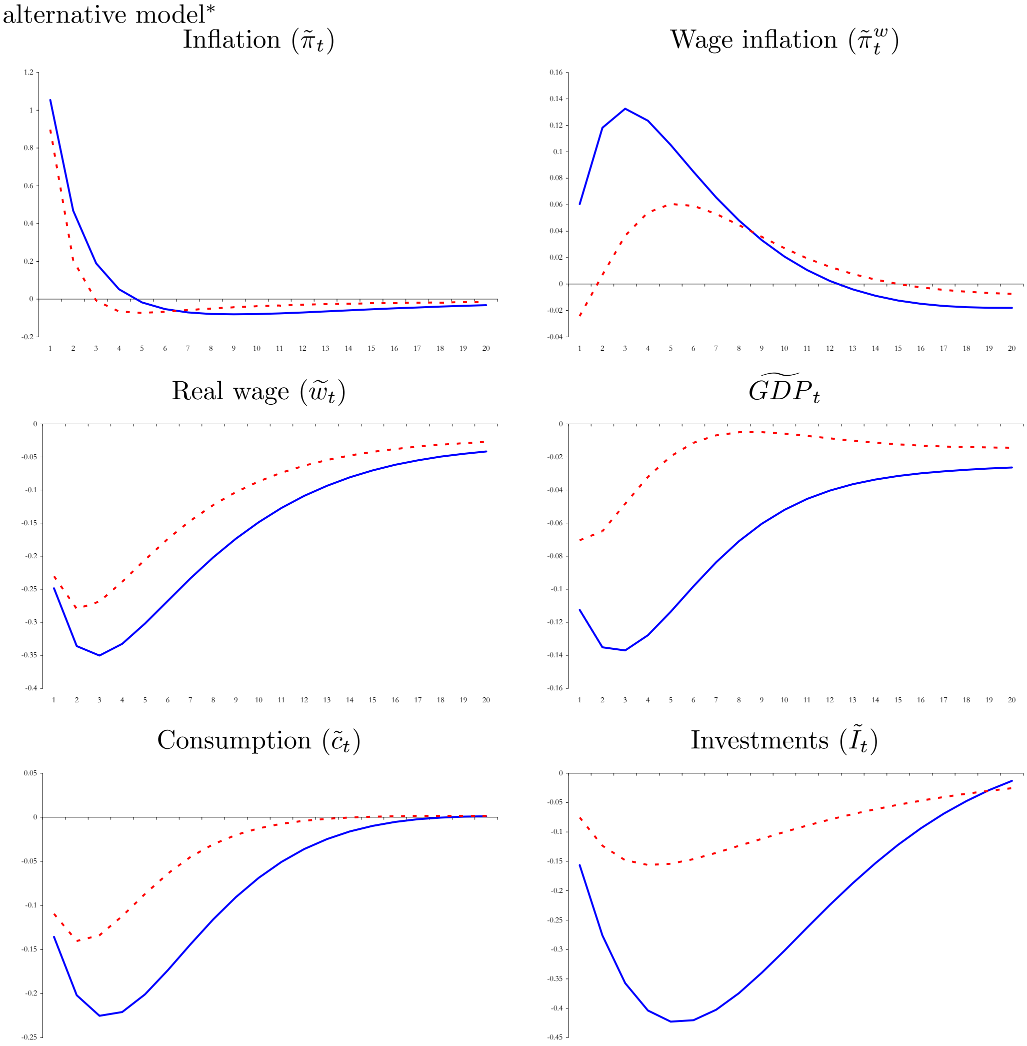
* solid: baseline model, dashed: alternative model

Figure 3.19 Monetary policy rule shock in the baseline model and in the alternative model*



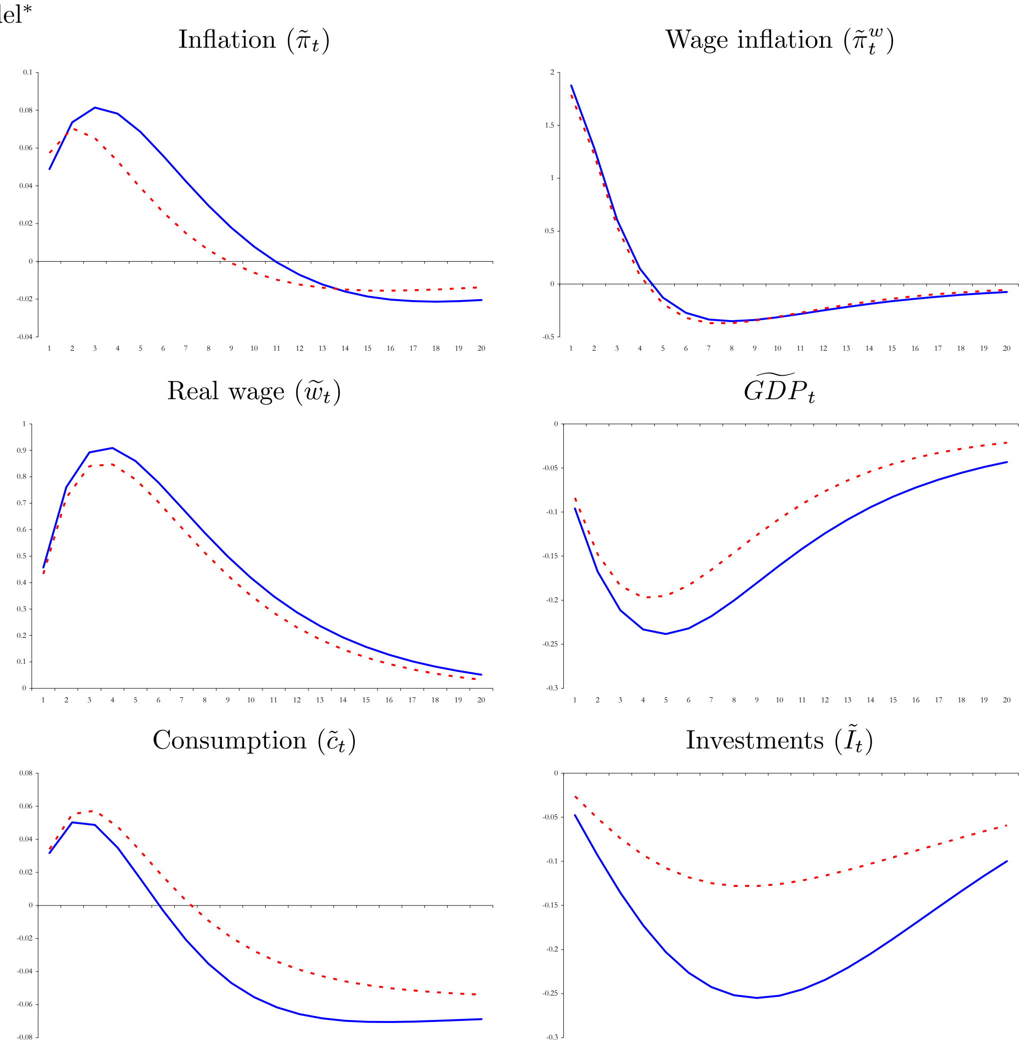
* solid: baseline model, dashed: alternative model

Figure 3.20 Consumer price markup shock in the baseline model and in the alternative model*



* solid: baseline model, dashed: alternative model

Figure 3.21 Labor market shock in the baseline model and in the alternative model*



* solid: baseline model, dashed: alternative model

3.7.2 Variance decomposition in the alternative model

As far as variance decompositions are concerned, one can observe that inflation is highly determined by the shock to the *'perceived underlying inflation'*, both in the short and in the long run (see *Table 3.14-3.17*). In the long run, more than 90 per cent of variance of inflation is explained by the consumer price markup and the 'perceived underlying inflation' shock. Disturbingly, the shock to the 'perceived underlying inflation' explains the variance of cyclical inflation by more than 25 per cent in 1 year and by around 80 per cent in the long run. Hence, the alternative model gives very little explanatory role for all other shocks. This is in sharp contrast to the case with the *baseline* model, where only around 65 per cent is explained by the consumer price markup shock. This clearly shows, that the *baseline* model explains inflation to a larger extent by structural shocks while in the *alternative* model large part of inflation variance can only be captured with shifts in the Phillips curve (with exogenous - not modelled - shocks). That is, the endogenous learning process in this *baseline* model was able to capture longer term inflation movements without introducing an additional exogenous shock related to disinflation. At the same time, it was also shown that this solution did not biased the indexation parameters downwards.

Similarily to the *baseline* model: real variables are highly influenced by external demand and productivity shocks in the long run and the real effects of financial premium and monetary-policy shocks are found negligible in the *alternative* model.

Table 3.14 Forecast error variance decomposition, model without adaptive learning $t = 1$ (one quarter)*

	$\tilde{g}_t$	$\widetilde{P}_t^{m*}$	$\tilde{\chi}_t$	$\tilde{x}_t^*$	$\widetilde{A}_t$	$\tilde{\upsilon}_t$	$\tilde{\upsilon}_t^w$	$\tilde{\upsilon}_t^x$	$\tilde{\varepsilon}_t^c$	$\tilde{\varepsilon}_t^{pr}$	$\tilde{\varepsilon}_t^r$	$\tilde{\varepsilon}_t^n$	$\tilde{\varepsilon}_t^I$	$\tilde{\varepsilon}_t^Q$	$\tilde{\varepsilon}_{kt}$
$\hat{\pi}_t$	0.7	0.2	7.7	1.1	7.8	71.8	2.1	1.0	2.2	1.1	0.1	0.0	4.1	0.0	0.1
$\hat{\pi}_t^x$	0.1	0.1	0.0	5.5	5.4	0.0	0.2	88.5	0.1	0.1	0.0	0.0	0.1	0.0	0.0
$\hat{\pi}_t^w$	0.2	0.2	0.6	0.8	1.6	0.0	93.5	0.8	1.1	0.7	0.1	0.0	0.5	0.0	0.0
$\bar{\pi}_t$ **	0.0	0.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
π_t^{***}	0.5	0.1	34.5	0.8	5.5	50.9	1.5	0.7	1.5	0.8	0.1	0.0	2.9	0.0	0.0
$\tilde{q}_t$	0.0	1.0	0.6	4.1	0.0	4.1	0.0	0.2	0.3	85.5	3.9	0.0	0.1	0.0	0.2
$\tilde{e}_t$	0.0	1.1	0.4	3.6	0.1	0.7	0.0	0.4	0.1	89.3	4.2	0.0	0.0	0.0	0.2
$d\tilde{e}_t$	0.0	1.1	0.4	3.6	0.1	0.7	0.0	0.4	0.1	89.3	4.2	0.0	0.0	0.0	0.2
$\hat{\imath}_t$	0.3	0.1	0.8	0.3	3.7	32.0	1.0	0.5	0.9	2.3	56.0	0.0	1.9	0.0	0.0
$\tilde{c}_t^{no}$	5.0	4.6	0.1	7.7	55.8	1.9	13.9	2.4	1.0	6.0	0.5	0.0	1.2	0.0	0.0
$\tilde{c}_t^o$	0.1	1.2	0.0	1.5	0.9	0.5	2.0	1.0	91.2	0.4	0.7	0.0	0.3	0.0	0.2
$\widetilde{w}_t$	0.0	0.2	0.0	0.5	0.5	3.7	93.5	0.5	0.5	0.4	0.0	0.0	0.1	0.0	0.0
$\tilde{x}_t$	0.0	0.0	0.0	83.6	0.9	0.0	0.0	15.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$\widetilde{m}_t^d$	12.0	3.7	0.0	4.5	68.2	0.0	2.2	0.2	2.3	3.7	0.0	0.0	3.1	0.0	0.0
$\widetilde{m}_t^x$	0.6	2.3	0.0	35.2	53.2	0.0	0.9	5.4	0.2	2.0	0.1	0.0	0.2	0.0	0.0
$\tilde{l}_t^d$	12.5	4.0	0.1	1.2	70.6	0.2	2.1	0.3	1.3	4.7	0.5	0.0	2.7	0.0	0.0
$\tilde{l}_t^x$	0.5	5.5	0.0	24.6	52.5	0.1	3.8	5.7	0.0	6.9	0.4	0.0	0.0	0.0	0.0
$\tilde{n}_t$	1.4	2.2	0.1	3.7	15.7	0.1	10.4	3.9	0.4	3.4	0.2	56.9	1.5	0.0	0.0
$\tilde{k}_t$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	20.9	0.0	78.9
$\tilde{I}_t$	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.0	0.1	0.2	0.1	0.0	99.2	0.0	0.0
$\tilde{b}_t$	3.0	22.1	0.0	14.9	41.3	0.0	0.9	14.5	0.6	2.0	0.0	0.0	0.7	0.0	0.0
$\widetilde{Q}_t$	0.0	0.2	1.8	3.9	0.8	26.4	0.4	5.4	0.0	4.1	27.6	0.0	14.6	13.3	1.5
$\tilde{r}_t^k$	6.4	1.2	0.0	11.3	73.8	0.4	0.4	2.2	0.9	1.7	0.2	0.0	1.4	0.0	0.0
P_t^x	0.1	0.1	0.0	5.5	5.4	0.0	0.2	88.5	0.1	0.1	0.0	0.0	0.1	0.0	0.0

* Calculated at mean parameter values, $^{**}d\bar{q}_t = -\bar{\pi}_t$ in IT, $^{***}\pi_t = \hat{\pi}_t + \bar{\pi}_t$

Table 3.15 Forecast error variance decomposition, model without adaptive learning $t = 4$ (one year)*

	$\tilde{g}_t$	$\widetilde{P}_t^{m*}$	$\tilde{\chi}_t$	$\tilde{x}_t^*$	$\widetilde{A}_t$	$\tilde{\upsilon}_t$	$\tilde{\upsilon}_t^w$	$\tilde{\upsilon}_t^x$	$\tilde{\varepsilon}_t^c$	$\tilde{\varepsilon}_t^{pr}$	$\tilde{\varepsilon}_t^r$	$\tilde{\varepsilon}_t^n$	$\tilde{\varepsilon}_t^I$	$\tilde{\varepsilon}_t^Q$	$\tilde{\varepsilon}_{kt}$
$\hat{\pi}_t$	0.6	0.2	27.7	1.8	6.2	39.6	5.1	2.0	4.8	2.0	0.2	0.0	9.6	0.0	0.2
$\hat{\pi}_t^x$	0.1	0.1	0.0	9.0	5.6	0.0	0.6	84.2	0.1	0.2	0.0	0.0	0.1	0.0	0.0
$\hat{\pi}_t^w$	0.1	0.2	2.0	0.8	1.2	0.0	90.8	1.4	1.4	1.0	0.1	0.0	1.1	0.0	0.0
$\bar{\pi}_t$ **	0.0	0.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
π_t^{***}	0.5	0.1	40.4	1.5	5.1	32.6	4.2	1.6	4.0	1.7	0.2	0.0	7.9	0.0	0.2
$\tilde{q}_t$	0.0	1.6	0.9	7.2	0.0	3.9	0.1	0.2	0.7	81.9	2.5	0.0	0.4	0.0	0.5
$\tilde{e}_t$	0.1	2.0	0.4	4.9	0.6	0.4	0.2	0.9	0.1	87.2	2.8	0.0	0.2	0.0	0.3
$d\tilde{e}_t$	0.0	1.0	0.3	3.3	0.2	1.2	0.1	0.4	0.2	88.2	4.6	0.0	0.2	0.0	0.2
$\hat{\imath}_t$	0.6	0.4	0.8	1.2	6.5	25.7	5.9	2.7	5.3	8.7	31.0	0.0	11.1	0.0	0.2
$\tilde{c}_t^{no}$	1.9	2.9	0.2	6.6	21.0	2.4	46.0	9.0	2.0	5.5	0.3	0.0	2.1	0.0	0.1
$\tilde{c}_t^o$	0.1	2.2	0.0	2.6	1.6	0.5	4.1	2.1	84.3	0.7	0.5	0.0	0.8	0.0	0.5
$\widetilde{w}_t$	0.0	0.1	0.1	0.4	0.1	1.6	95.4	0.9	0.6	0.5	0.0	0.0	0.1	0.0	0.0
$\tilde{x}_t$	0.0	0.1	0.0	49.3	4.0	0.0	0.6	45.6	0.1	0.2	0.0	0.0	0.1	0.0	0.0
$\widetilde{m}_t^d$	7.6	4.9	0.0	7.9	43.9	0.2	11.5	2.0	7.3	4.5	0.0	0.0	10.0	0.0	0.0
$\widetilde{m}_t^x$	0.3	2.6	0.0	37.7	25.5	0.0	3.2	28.8	0.3	1.4	0.0	0.0	0.2	0.0	0.0
$\tilde{l}_t^d$	8.8	3.8	0.1	1.6	50.4	0.4	15.7	1.2	3.8	5.1	0.5	0.0	8.4	0.0	0.0
$\tilde{l}_t^x$	0.2	3.8	0.0	21.6	23.1	0.0	19.7	24.7	0.1	6.4	0.2	0.0	0.0	0.0	0.0
$\tilde{n}_t$	0.5	1.6	0.1	2.1	5.3	0.0	22.3	6.1	0.5	3.0	0.2	56.3	2.0	0.0	0.0
$\tilde{k}_t$	0.0	0.0	0.1	0.0	0.1	0.1	0.2	0.0	0.1	0.2	0.0	0.0	45.0	0.0	54.3
$\tilde{I}_t$	0.0	0.0	0.1	0.0	0.2	0.2	0.4	0.0	0.2	0.6	0.1	0.0	97.9	0.0	0.1
$\tilde{b}_t$	1.4	19.0	0.0	31.0	17.0	0.0	3.4	23.4	1.3	1.8	0.0	0.0	1.7	0.0	0.0
$\widetilde{Q}_t$	0.4	0.6	1.8	1.5	5.2	19.0	3.4	2.3	1.6	7.7	13.9	0.0	36.7	4.3	1.6
$\tilde{r}_t^k$	4.5	1.1	0.1	16.7	50.9	0.7	1.7	15.3	2.7	2.5	0.3	0.0	3.5	0.0	0.1
P_t^x	0.1	0.2	0.0	16.3	6.6	0.0	1.1	75.0	0.3	0.3	0.0	0.0	0.2	0.0	0.0

* Calculated at mean parameter values, $^{**}d\bar{q}_t = -\bar{\pi}_t$ in IT, $^{***}\pi_t = \hat{\pi}_t + \bar{\pi}_t$

Table 3.16 Forecast error variance decomposition, model without adaptive learning $t = 10$ (ten quarters)*

	$\tilde{g}_t$	$\widetilde{P}_t^{m*}$	$\tilde{\chi}_t$	$\tilde{x}_t^*$	$\widetilde{A}_t$	$\tilde{\upsilon}_t$	$\tilde{\upsilon}_t^w$	$\tilde{\upsilon}_t^x$	$\tilde{\varepsilon}_t^c$	$\tilde{\varepsilon}_t^{pr}$	$\tilde{\varepsilon}_t^r$	$\tilde{\varepsilon}_t^n$	$\tilde{\varepsilon}_t^I$	$\tilde{\varepsilon}_t^Q$	$\tilde{\varepsilon}_{kt}$
$\hat{\pi}_t$	0.4	0.2	49.4	1.2	4.4	26.2	3.8	1.4	3.5	1.5	0.2	0.0	7.4	0.0	0.4
$\hat{\pi}_t^x$	0.1	0.2	0.0	10.1	6.1	0.0	0.6	82.4	0.2	0.2	0.0	0.0	0.2	0.0	0.0
$\hat{\pi}_t^w$	0.1	0.2	4.2	0.8	1.1	0.0	88.8	1.4	1.3	0.9	0.1	0.0	1.1	0.0	0.0
$\bar{\pi}_t$ **	0.0	0.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
π_t^{***}	0.4	0.2	55.5	1.1	3.8	23.0	3.4	1.3	3.1	1.3	0.2	0.0	6.5	0.0	0.3
$\tilde{q}_t$	0.0	3.7	1.3	12.1	0.6	3.1	0.2	1.1	0.7	73.7	1.9	0.0	0.5	0.0	0.9
$\tilde{e}_t$	0.2	3.5	0.3	5.8	2.4	1.2	2.7	2.9	1.2	72.9	2.0	0.0	4.7	0.0	0.3
$d\tilde{e}_t$	0.0	1.0	0.3	3.3	0.2	1.2	0.3	0.4	0.3	87.6	4.5	0.0	0.5	0.0	0.2
$\hat{\imath}_t$	0.5	0.3	0.6	1.1	5.1	19.0	9.1	2.9	7.4	12.8	22.9	0.0	17.6	0.0	0.7
$\tilde{c}_t^{no}$	1.3	2.3	0.4	4.5	14.0	2.1	57.1	8.3	2.0	5.1	0.3	0.0	2.5	0.0	0.1
$\tilde{c}_t^o$	0.2	4.6	0.0	6.4	2.5	0.4	8.4	4.2	69.6	0.8	0.4	0.0	1.3	0.0	1.2
$\widetilde{w}_t$	0.0	0.2	0.1	0.2	0.1	1.2	95.2	1.0	0.7	0.8	0.0	0.0	0.3	0.0	0.1
$\tilde{x}_t$	0.0	0.2	0.0	43.0	4.7	0.0	1.9	49.1	0.4	0.4	0.0	0.0	0.2	0.0	0.1
$\widetilde{m}_t^d$	6.3	5.9	0.1	8.2	36.6	0.4	15.1	2.0	8.2	4.7	0.1	0.0	12.5	0.0	0.1
$\widetilde{m}_t^x$	0.3	3.0	0.0	34.5	23.7	0.0	4.0	32.7	0.3	1.3	0.0	0.0	0.2	0.0	0.0
$\tilde{l}_t^d$	7.0	3.1	0.2	1.3	40.1	0.3	28.5	1.1	3.7	4.2	0.5	0.0	9.9	0.0	0.1
$\tilde{l}_t^x$	0.2	3.2	0.0	17.7	17.6	0.1	31.9	22.9	0.4	5.7	0.2	0.0	0.1	0.0	0.0
$\tilde{n}_t$	0.3	1.2	0.2	1.2	2.6	0.0	34.5	4.6	0.3	2.2	0.1	50.8	2.1	0.0	0.0
$\tilde{k}_t$	0.0	0.1	0.2	0.0	0.2	0.2	0.7	0.0	0.3	0.8	0.1	0.0	64.9	0.0	32.5
$\tilde{I}_t$	0.0	0.1	0.5	0.0	0.3	0.3	1.5	0.1	0.7	1.6	0.1	0.0	94.2	0.0	0.5
$\tilde{b}_t$	0.8	18.4	0.0	38.1	9.5	0.1	7.6	17.8	2.3	2.2	0.0	0.0	3.2	0.0	0.0
$\widetilde{Q}_t$	0.2	0.5	1.3	0.9	3.4	10.8	4.7	1.9	2.4	7.1	7.8	0.0	55.2	2.4	1.3
$\tilde{r}_t^k$	4.2	1.0	0.2	15.7	47.7	0.8	2.0	17.6	3.2	2.9	0.3	0.0	3.7	0.0	0.6
P_t^x	0.1	0.2	0.0	22.6	6.2	0.0	2.3	67.2	0.5	0.4	0.0	0.0	0.3	0.0	0.2

* Calculated at mean parameter values, $^{**}d\bar{q}_t = -\bar{\pi}_t$ in IT, $^{***}\pi_t = \hat{\pi}_t + \bar{\pi}_t$

Table 3.17 Unconditional variance decomposition, model without adaptive learning*

	$\tilde{g}_t$	$\widetilde{P}_t^{m*}$	$\tilde{\chi}_t$	$\tilde{x}_t^*$	$\widetilde{A}_t$	$\tilde{\upsilon}_t$	$\tilde{\upsilon}_t^w$	$\tilde{\upsilon}_t^x$	$\tilde{\varepsilon}_t^c$	$\tilde{\varepsilon}_t^{pr}$	$\tilde{\varepsilon}_t^r$	$\tilde{\varepsilon}_t^n$	$\tilde{\varepsilon}_t^I$	$\tilde{\varepsilon}_t^Q$	$\tilde{\varepsilon}_{kt}$
$\hat{\pi}_t$	0.1	0.1	83.6	0.4	1.3	7.6	1.3	0.5	1.1	0.5	0.1	0.0	3.2	0.0	0.2
$\hat{\pi}_t^x$	0.1	0.2	0.0	10.1	6.1	0.0	0.7	82.2	0.2	0.2	0.0	0.0	0.2	0.0	0.0
$\hat{\pi}_t^w$	0.1	0.2	17.9	0.6	0.9	0.0	75.8	1.2	1.2	0.8	0.1	0.0	1.1	0.0	0.0
$\bar{\pi}_t$ **	0.0	0.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
π_t^{***}	0.1	0.1	84.2	0.4	1.3	7.3	1.3	0.5	1.1	0.4	0.1	0.0	3.1	0.0	0.2
$\tilde{q}_t$	0.3	13.7	4.8	28.4	4.1	1.1	8.6	8.0	1.9	23.2	0.5	0.0	4.6	0.0	0.7
$\tilde{e}_t$	0.4	6.2	0.6	8.2	4.0	1.4	11.9	6.0	5.1	39.7	1.1	0.0	13.1	0.0	2.4
$d\tilde{e}_t$	0.0	1.0	0.3	3.3	0.2	1.2	0.3	0.4	0.3	87.3	4.5	0.0	0.8	0.0	0.2
$\hat{\imath}_t$	0.5	0.7	0.6	1.8	4.8	17.5	8.6	3.0	7.0	12.4	20.6	0.0	21.3	0.0	1.4
$\tilde{c}_t^{no}$	1.1	3.3	4.8	6.6	12.2	1.9	51.2	7.8	1.8	4.9	0.2	0.0	4.0	0.0	0.3
$\tilde{c}_t^o$	0.5	14.7	0.1	26.2	5.3	0.2	15.1	9.8	23.7	1.8	0.1	0.0	0.8	0.0	1.7
$\widetilde{w}_t$	0.0	0.3	2.5	0.7	0.1	1.2	90.4	1.1	0.7	1.0	0.0	0.0	1.6	0.0	0.4
$\tilde{x}_t$	0.1	1.3	0.4	41.8	4.6	0.0	2.5	45.5	0.5	0.7	0.0	0.0	2.1	0.0	0.4
$\widetilde{m}_t^d$	4.3	10.4	0.2	17.7	26.0	0.3	14.5	5.5	6.4	4.3	0.0	0.0	10.0	0.0	0.3
$\widetilde{m}_t^x$	0.3	3.3	0.0	34.5	23.4	0.0	4.2	32.4	0.3	1.3	0.0	0.0	0.3	0.0	0.0
$\tilde{l}_t^d$	6.7	3.0	0.9	1.3	38.4	0.3	30.0	1.1	3.5	4.1	0.4	0.0	10.1	0.0	0.2
$\tilde{l}_t^x$	0.2	6.5	0.2	21.6	15.2	0.1	28.8	20.4	1.0	5.2	0.1	0.0	0.6	0.0	0.1
$\tilde{n}_t$	0.3	3.2	0.9	5.3	2.8	0.0	33.9	5.0	0.6	2.2	0.1	43.7	1.9	0.0	0.2
$\tilde{k}_t$	0.0	0.5	13.9	0.2	0.5	0.4	3.9	0.5	1.7	3.1	0.1	0.0	61.4	0.0	13.7
$\tilde{I}_t$	0.0	0.2	3.2	0.1	0.3	0.3	2.4	0.3	1.1	2.5	0.1	0.0	87.8	0.0	1.6
$\tilde{b}_t$	0.5	19.0	0.5	36.5	6.4	0.2	14.7	12.4	3.4	3.5	0.0	0.0	2.2	0.0	0.6
$\widetilde{Q}_t$	0.2	0.4	1.1	0.7	2.8	9.0	4.1	1.6	2.1	6.1	6.5	0.0	62.1	2.0	1.1
$\tilde{r}_t^k$	3.8	1.4	0.4	15.2	44.1	0.8	2.5	16.5	3.2	2.9	0.3	0.0	7.5	0.0	1.5
P_t^x	0.1	1.4	0.4	23.3	6.1	0.0	2.8	61.9	0.6	0.8	0.0	0.0	2.2	0.0	0.4

* Calculated at mean parameter values, $^{**}d\bar{q}_t = -\bar{\pi}_t$ in IT, $^{***}\pi_t = \hat{\pi}_t + \bar{\pi}_t$

3.8 Conclusions

In this chapter I present an estimated two-sector dynamic stochastic general equilibrium (DSGE) small-open-economy model for the Hungarian economy. The speciality of the model is that agents' perception on underlying inflation is made endogenous by a real-time adaptive-learning algorithm. In addition, the monetary regime shift occured in 2001 is explicitely taken into account. The model is estimated by Bayesian methods.

The model's special feature is that inflation to which rule-of-thumb price setters partly indexate is generated by an adaptive learning mechanism. In this model, agents' perception on *'underlying'* inflation heavily influences long term inflation developments.

According to the estimates the Calvo parameters of consumer prices are similar to those estimated for the euro-area. On the other hand, nominal wage rigidities are less important in Hungary than in the euro-area. An interesting result is that the change in monetary regime mostly influenced the price indexation mechanisms in the economy. Less role for indexation in consumer prices are estimated for the inflation targeting regime than in the previous crawling peg regime. Wage indexation parameters are estimated to be relatively low compared to euro zone estimates.

Interest-rate smoothing parameter is found significantly lower than the euro-area and US estimates. The real-time adaptive learning process of underlying inflation works as an additional source of inflation inertia and it is also important in the responses of real variables, as well. Adjustment cost of investment is found to be higher usually found in the literature. This results in reactions of investment to shocks being close in magnitude of output or consumption. Comparing impulse responses with other DSGE models, monetary policy and productivity shocks have qualitatively similar effect. The basic difference is that in this model investments are less responsive than usual in the literature. A crowding-out effect of a government-consumption shock in the medium run is also found. Though, the presence of non-optimizer consumers create a weekly Keynesian effect of fiscal shock in the short run.

According to variance decomposition, both the *cyclical* and the permanent (*'underlying'*) component of inflation can be explained by productivity, investment, consumer preference and markup shocks. Unlike in other estimated DSGE models estimated for disinflation periods, by introducing a simple learning scheme, the model was capable to explain the disinflation process occured in Hungary. As suspected in a small, open economy, real variables are highly influenced by external demand and productivity shocks in the long run. Real effects of financial premium and monetary-policy shock are negligible, which is in contrast with eurozone estimates of Smets and Wouters (2003). However, it conforms to the results of Vonnák (2007) and Jakab et al (2006) that monetary transmission mechanism in Hungary works less through the change in output.

As a robustness check the estimates of an *alternative* model without endogenous real time adaptive learning of *'underlying inflation'* is also demonstrated. The estimated coefficients in the *baseline* and in the *alternative* model are found to be relatively close to each other. The degree of indexation of consumer prices is estimated to be slightly lower in the alternative model indicating that the presence of adaptive learning is not responsible for an 'intrinsic' inertia in inflation. Impulse responses are more or less similar in different model specifications. Slight differences can be found with respect to nominal wage reactions and consumer prices. Wages behave in a more flexible manner in the *alternative* model, while consumer prices generally respond to a lesser extent in the alternative model than in the baseline model.

However, variance decomposition shows that negliging information content of long-term movements of inflation in a country with disinflation has serious consequences. It would lead to a model which can only explain long term inflationary movements in a limited way. The exogenous shock (inflation target shock) is responsible for a large part of inflation movements either in the short or in the long run.

References

[1] Adolfson, M., Laseén, S. , Lindé, J. and Villani, M. (2006), Bayesian Estimation of an Open Economy DSGE Model with Incomplete Pass-Through, Sveriges Riksbank Working Paper No. 179.

[2] Altissimo, F., Ehrmann, M. and Smets, F. (2006), Inflation Persistence and Price-Setting Behaviour in the Euro Area: A Summary of the IPN Evidence, ECB Occasional Paper No. 46.

[3] Ambler, S., Dib, A. and Rebei, N. (2003), Nominal Rigidities and Exchange Rate Pass-Through in a Structural Model of a Small Open Economy, Bank of Canada Working Paper No. 2003-29.

[4] An, S. and Schorfheide, F. (2005), Bayesian Analysis of DSGE models, CEPR Working Paper 5207.

[5] Bacchetta, P. and van Wincoop, E. (2003), Why do Consumer Prices React Less Than Import Prices to Exchange Rates, *Journal of the European Economic Association*, 1 (2-3), pp.:662-670.

[6] Barhoumi, K. (2006), Differences in long run exchange rate pass-through into import prices in developing countries: An empirical investigation, *Economic Modelling* 23, pp: 926-951, 2006

[7] Benigno, P. and Woodford, M. (2003), Optimal Monetary and Fiscal Policy: A Linear-Quadratic Approach, NBER Macroeconomics Annual 2003

[8] Benk, Sz., Jakab, M. Z, and Vadas, G. (2005), Potential Output Estimations for Hungary:A Survey of Different Approaches, MNB Occasional Paper No. 43.

[9] Benk, Sz., Jakab, M. Z, Kovács, M. A., Párkányi, B., Reppa Z. and Vadas, G. (2006), The Hungarian Quarterly Projection Model (NEM), Magyar Nemzeti Bank, Occassional Papers No. 60.

[10] Bils, M. and Klenow, P. J. (2004), Some Evidence on the Importance of Sticky Prices, *Journal of Political Economy*, 112, 947-85.

[11] Boukez, H. and Rebei,N. (2005), Has Exchange Rate Pass-Through Really Declined in Canada?, mimeo.

[12] Brooks, S.P. and Gelman, A. (1998), General Methods for Monitoring Convergence of Iterative Simulations, *Journal of Computational and Graphical Statistics* 7, 434-455.

[13] Campa, J. and Goldberg, L. (2002), Exchange Rate Pass-Through into Import Prices; A Macro or Micro Phenomenon, NBER Working Paper No. 8934.

[14] Campa, J. and Goldberg, L. (2006), Pass-Through of Exchange Rates to Consumption Prices: What Has Changed and Why?, NBER Working Paper No. 12547.

[15] Campolmi, A. (2006) Which inflation to target? A small open economy with sticky wages indexed to past inflation, Department of Economics, Universitat Pompeu Fabra, mimeo

[16] Calvo, G. (1983), Staggered Prices in a Utility Maximizing Framework, *Journal of Monetary Economics,* 1983, 12(3), pp. 383-98.

[17] Clarida, R., Gali,J. and Gertler, M. (2001), Optimal Monetary Policy in Open versus Closed Economies: An Integrated Approach, *AEA Papers and Proceedings*, May 2001, (91) No. 2

[18] Christiano, L.J., Eichenbaum, M. and Evans, C. L. (2005), Nominal Rigidities and the Dynamic Effects of a Shock to Monetary Policy, *Journal of Political Economy* 113(1), 1-45.

[19] Christoffel, K, Coenen.G. and Warne, A. (2007), The New Area-Wide Model of the Euro Area:Specification and Estimation Results, mimeo

[20] Choudri, E. U. and Hakura, D. S. (2006), Exchange rate pass-through to domestic prices: Does the inflationary environment matter?, *Journal of International Money and Finance*, 25, pp.: 614-639.

[21] Clarida, R., Galí, J. and Gertler, M. (1999), The Science of Monetary Policy: A New Keynesian Perspective, *Journal of Economic Literature* 37(4), December 1661-1707.

[22] Convergence Report, Magyar Nemzei Bank, 2006

[23] Corsetti, G., Dedola, L. and Le Duc, S. (2006), DSGE Models of High Exchange Rate Variability and Low Pass-Through, paper presented at SED, Budapest

[24] Corsetti, G. and Pesenti, P. (2002), International Dimensions of Optimal Monetary Policy, *Journal of Monetary Economics*

[25] Corsetti, G. and Pesenti, P. (2004), Endogenous Pass-Through And Optimal Monetary Policy: A Model of Self-Validating Exchange Rate Regimes, mimeo

[26] Devereux, M. and Engel, Ch. (2003), Monetary Policy in the Open Economy Revisited: Price Setting and Exchange Rate Flexibility, *Review of Economic Studies,* 70 (4). pp: 765-783.

[27] Devereux, M., Engel, Ch. and Stoorgard, P. (2004), Endogenous Exchange Rate Pass-Through When Nominal Prices are Set in Advance, *Journal of International Economics,* 63. pp: 263-291.

[28] Devereux, M. and Yetman, J. (2002), Price-Setting and Exchange Rate Pass-Through: Theory and Evidence Proceedings of a Conference Held at the Bank of Canada, November 2002, http://www.bankofcanada.ca/en/conference/2002/Devereux_Yetman-v3.pdf

[29] Dickens, W. T., Lorenz, G., Groshen, E. L., Holden, S., Messina, J., Schweitzer,M. E., Turunen, J., and Ward, M. (2006), The Interaction of Labour Markets and Inflation: Micro Evidence from the International Wage Flexibility Project, paper presented at BESS at the Magyar Nemzeti Bank, *htttp://english.mnb.hu/Engine.aspx?page=mnben_seminar&ContentId=9631*

[30] Dornbusch, R. (1987) 'Exchange rate and prices', *American Economic Review* 77, 93–106, March 1987

[31] Erceg, J.C, Guerrieri, L. and Gust, C. (2006), 'SIGMA: A New Open Economy Model for Policy Analysis', *International Journal of Central Banking*, March 2006

[32] Erceg, C., Henderson, D. and Levin, A. (2000), 'Optimal Monetary Policy with Staggered Wage and Price Contracts', *Journal of Monetary Economics*, 46, pp: 281-313

[33] Frenkel, J. A., Parsley, D. C., Shang-Jin, W. (2005), Slow Passthrough Around the World: A New Import for Developing Countries?, KGS Working Paper No. RWP05-16, February 2005

[34] Gagnon, J. and Ihrig, J. (2004), Monetary Policy and Exchange Rate Pass-Through, Board of Governors of the Federal Reserve System, International Finance Discussion Papers No. 704.

[35] Galí, J. and Monacelli, T. (2005), Monetary Policy and Exchange Rate Volatility in a Small Open Economy, *Review of Economic Studies*, Blackwell Publishing, vol. 72(3), pages 707-734, 07.

[36] Geweke, J. (1998), Using Simulation Methods for Bayesian Econometric Models: Inference, Development and Communication, mimeo. University of Minnesota and Federal Reserve Bank of Minneapolis.

[37] Goldberg, L. (2005), Trade Invoicing in the Accession Countries: Are They Suited to the Euro?, Federal Reserve Bank of New York Staff Reports, No. 222, October 2005.

[38] Gopinath, G., Ishkoki, O. and Rigobon, R. (2007), Currency Choice and Exchange Rate Pass-Through, NBER Working Papers, No. 13432, September 2007.

[39] Goodhart, Ch. (2004), Gradualism in the Adjustment of Official Interest Rates: Some Partial Explanations, *Financial Markets Group Special Paper* 157, London School of Economics

[40] Gust, C. and Sheets, N. (2006), The Adjustment of Global External Imbalances: Does Partial Pass-Through to Trade Prices Matter?, Board of Governors of the Federal Reserve System, International Finance Discussion Papers No. 850.

[41] Hamilton, J.D. (1994), *Time Series Analysis*, Princeton, NJ: Princeton University Press.

[42] Hidi, J. (2006), A magyar monetáris politikai reakciófüggvény becslése, *Közgazdasági Szemle*, LIII. pp.: 1178-1199

[43] Holden, S. and Wulfsberg, F. (2007), Are real wages rigid downwards?, 28th March, mimeo, http://folk.uio.no/sholden/

[44] Jakab, M. Z., Várpalotai, V. and Vonnák, B. (2006), How does monetary policy affect aggregate demand? A multimodel approach for Hungary, Magyar Nemzeti Bank Working Paper Series, 2006/4.

[45] Jakab, M. Z. (2007), Endogenous Exchange Rate Pass-Through with Imported Intermediates, Central European University, mimeo

[46] Jakab, M. Z. and Kónya, I. (2008), An Open Economy DSGE Model with Labor Market Frictions, paper presented at 6th Macroeconomic Policy Research Workshop on Labor markets, Wage Behavior and Inflation Dynamics, Magyar Nemzeti Bank, November 2007

[47] Jakab, M. Z. and Világi, B. (2008), An Estimated DSGE Model of the Hungarian Economy, Magyar Nemzeti Bank, mimeo

[48] Kamps, A. (2006), The Euro as Invoicing Currency in International Trade, ECB. Working Paper Series No. 665, August 2006

[49] Kónya, I. (2007), Structural Determinants of Exchange Rate Pass-Through, Magyar Nemzeti Bank, mimeo

[50] Koopman, S.J. and Durbin, J. (2003), Filtering and Smoothing of State Vector for Diffuse State-Space Models, *Journal of Time Series Analysis* 24(1), 86-98.

[51] Kuntsevich, A. and Kappel, F. (1997), SolvOpt – The Solver For Local Nonlinear Optimization Problems, Institute for Mathematics, Karl-Franzens University of Graz.

[52] Lane, Ph. (2000), The New Open Economy Macroeconomics: A Survey, *Journal of International Economics*, 54, pp.: 235-266.

[53] Laxton, D. and Pesenti, P. (2003), Monetary Rules for Small, Open, Emerging Economies, NBER Working Paper 9568.

[54] McCallum, B. and Nelson, E. (2001), Monetary Policy for an Open Economy: An Alternative Framework with Optimizing Agents and Sticky Prices, NBER Working Paper, No. 8175.

[55] Lubick, T. and Schorfheide, F. (2004), Testing for Indeterminacy: An Application to US Monetary Policy, *American Economic Review*, 94, 190-217.

[56] Maih, J. (2006), Wage-Price Dynamics in a DSGE Model with Imperfect Exchange Rate Pass-Through, www.cepremap.cnrs.fr/juillard/paris06/wpdsgeparisabs.pdf

[57] Monacelli, T. (2003), Monetary Policy in a Low Pass-Through Environment, *Journal of Money, Credit and Banking*

[58] Monacelli, T. (2003), Monetary Policy in a Low Pass-Through Environment, ECB Working Paper Series, No. 227, April 2003

[59] Rabanal, P. and Rubio-Ramirez, J.F. (2005), Comparing New Keynesian Models in the Euro Area: A Bayesian Approach, Federal Reserve Bank of Atlanta Working Paper 2003-30a.

[60] Schmitt-Grohe, S. and Uribe, M. (2003), Closing Small Open Economy Models, *Journal of International Economics*, 61, 163-185.

[61] Schorfheide, F. (2000), Loss Function-Based Evaluation of DSGE models, *Journal of Applied Econometrics* 15, 645-670.

[62] Sekine, T. (2006), Time-varying exchange rate pass-through: experiences of some industrial countries, BIS Working Papers No. 202.

[63] Smets, F. and Wouters, R. (2002), Opennes, imperfect exchange rate pass-through and monetary policy, *Journal of Monetary Economics*, 49. pp.: 947-981.

[64] Smets, F. and Wouters, R. (2003), An Estimated Stochastic Dynamic General Equilibrium Model of the Euro Area, *Journal of the European Economic Association* 1, 1123-1175.

[65] Taylor, J. (2000), Low Inflation, Pass-Through, and the Pricing Power of Firms, *European Economic Review*, 44 (7). pp.: 1195-1408.

[66] Uhlig, H. (1999), A Toolkit for Analyzing Dynamic Stochastic Models Easily, in: *Computational Methods for the Study of Dynamic Economies*, eds. R. Marimon and A. Scott, Oxford: Oxford University Press.

[67] Világi, B. (2004), Dual inflation and real exchange rate in new open economy macroeconomics, Magyar Nemzeti Bank Working Papers, 2004/5.

[68] Világi, B. (2007), Adaptive Learning and Macroeconomic Persistence: Comparing DSGE models of the Euro Area, mimeo. Magyar Nemzeti Bank.

[69] Vonnák, B. (2007), The Hungarian Monetary Transmission Mechanism: an Assessment, MNB Working Paper, 2007/3.

[70] Woodford, M. (2003), Interest and Prices: Foundations of a Theory of Monetary Policy, Princeton, NJ: *Princeton University Press.*

[71] Yun, T. (1996), Nominal Price Rigidity, Money Supply Endogeneity, and Business Cycles, *Journal of Monetary Economics* 37, 345-370.

A Appendix to chapter 1: Tables

Table A.1.1 Share of LCP price setters under productivity shocks (baseline monetary policy)

α	γ_w (nominal wage rigidity)								
(labour share)	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0.1	0.52	0.50	0.49	0.48	0.47	0.47	0.46	0.46	0.45
0.2	0.55	0.50	0.47	0.45	0.44	0.42	0.41	0.40	0.39
0.3	0.60	0.50	0.45	0.41	0.39	0.36	0.34	0.33	0.31
0.4	0.68	0.52	0.42	0.36	0.32	0.28	0.25	0.22	0.20
0.5	0.81	0.54	0.39	0.30	0.23	0.17	0.12	0.08	0.03
0.6	1.00	0.58	0.35	0.20	0.09	0.00	0.00	0.00	0.00
0.7	1.00	0.66	0.31	0.07	0.00	0.00	0.00	0.00	0.00
0.8	1.00	0.79	0.28	0.00	0.00	0.00	0.00	0.00	0.00
0.9	1.00	1.00	0.26	0.00	0.00	0.00	0.00	0.00	0.00

Table A.1.2 Short term pass-through to Home import price under productivity shocks (baseline monetary policy)

α	γ_w (nominal wage rigidity)								
(labour share)	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0.1	0.48	0.50	0.51	0.52	0.53	0.53	0.54	0.54	0.55
0.2	0.45	0.50	0.53	0.55	0.56	0.58	0.59	0.60	0.61
0.3	0.40	0.50	0.55	0.59	0.61	0.64	0.66	0.67	0.69
0.4	0.32	0.48	0.58	0.64	0.68	0.72	0.75	0.78	0.80
0.5	0.19	0.46	0.61	0.70	0.77	0.83	0.88	0.92	0.97
0.6	0.00	0.42	0.65	0.80	0.91	1.00	1.00	1.00	1.00
0.7	0.00	0.34	0.69	0.93	1.00	1.00	1.00	1.00	1.00
0.8	0.00	0.21	0.72	1.00	1.00	1.00	1.00	1.00	1.00
0.9	0.00	0.00	0.74	1.00	1.00	1.00	1.00	1.00	1.00

Table A.1.3 Share of LCP price setters under monetary rule shocks (baseline monetary policy)

α	γ_w (nominal wage rigidity)								
(labour share)	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0.1	0.49	0.48	0.48	0.47	0.47	0.46	0.46	0.45	0.45
0.2	0.49	0.46	0.45	0.44	0.42	0.42	0.41	0.40	0.39
0.3	0.49	0.45	0.42	0.39	0.37	0.36	0.34	0.32	0.31
0.4	0.51	0.43	0.38	0.34	0.31	0.28	0.25	0.22	0.19
0.5	0.55	0.43	0.34	0.27	0.22	0.17	0.12	0.08	0.03
0.6	0.60	0.43	0.30	0.19	0.09	0.00	0.00	0.00	0.00
0.7	0.66	0.45	0.26	0.07	0.00	0.00	0.00	0.00	0.00
0.8	0.74	0.50	0.22	0.00	0.00	0.00	0.00	0.00	0.00
0.9	0.82	0.57	0.19	0.00	0.00	0.00	0.00	0.00	0.00

Table A.1.4 Short term pass-through to Home import price under monetary rule shocks (baseline monetary policy)

α	γ_w (nominal wage rigidity)								
(labour share)	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0.1	0.51	0.52	0.52	0.53	0.53	0.54	0.54	0.55	0.55
0.2	0.51	0.54	0.55	0.56	0.58	0.58	0.59	0.60	0.61
0.3	0.51	0.55	0.58	0.61	0.63	0.64	0.66	0.68	0.69
0.4	0.49	0.57	0.62	0.66	0.69	0.72	0.75	0.78	0.81
0.5	0.45	0.57	0.66	0.73	0.78	0.83	0.88	0.92	0.97
0.6	0.40	0.57	0.70	0.81	0.91	1.00	1.00	1.00	1.00
0.7	0.34	0.55	0.74	0.93	1.00	1.00	1.00	1.00	1.00
0.8	0.26	0.50	0.78	1.00	1.00	1.00	1.00	1.00	1.00
0.9	0.18	0.43	0.81	1.00	1.00	1.00	1.00	1.00	1.00

Table A.1.5 Share of LCP-price setters under different monetary policies
($\alpha = 0.5$)

γ_w	Monetary rule shocks	Productivity shocks	Monetary rule shocks	Productivity shocks	Monetary rule shocks	Productivity shocks
	Baseline policy		More inflationary focused		Original Taylor	
0.1	0.70	1.00	0.71	1.00	0.70	0.79
0.2	0.65	1.00	0.66	1.00	0.64	0.72
0.3	0.59	0.94	0.60	1.00	0.58	0.63
0.4	0.52	0.73	0.53	1.00	0.51	0.55
0.5	0.44	0.56	0.46	0.87	0.43	0.46
0.6	0.36	0.42	0.38	0.55	0.35	0.37
0.7	0.28	0.30	0.29	0.35	0.27	0.28
0.8	0.19	0.19	0.20	0.21	0.19	0.19
0.9	0.10	0.10	0.10	0.10	0.10	0.10

Table A.1.6 Short-term exchange rate pass-through to import prices under different monetary policies
($\alpha = 0.5$)

γ_w	Monetary rule shocks	Productivity shocks	Monetary rule shocks	Productivity shocks	Monetary rule shocks	Productivity shocks
	Baseline policy		More inflationary focused		Original Taylor	
0.1	0.30	0.00	0.29	0.00	0.30	0.21
0.2	0.35	0.00	0.34	0.00	0.36	0.28
0.3	0.41	0.06	0.40	0.00	0.42	0.37
0.4	0.48	0.27	0.47	0.00	0.49	0.45
0.5	0.56	0.44	0.54	0.13	0.57	0.54
0.6	0.64	0.58	0.62	0.45	0.65	0.63
0.7	0.72	0.70	0.71	0.65	0.73	0.72
0.8	0.81	0.81	0.80	0.79	0.81	0.81
0.9	0.90	0.90	0.90	0.90	0.90	0.90

B Appendix to chapter 3

B.1 The model

B.1.1 Production

Cost minimization

First, let us show how to derive the log-linearized equations of the demand for production inputs. The marginal-cost equation (117) implies that

$$mc_t^s = A_t^{-1}\left[\bar{\alpha}_s\left(r_t^k\right)^{1-\varrho} + (1-\bar{\alpha}_s)\left(w_t^{zs}\right)^{1-\varrho}\right]^{\frac{1}{1-\varrho}}.$$

Log-linearizing it yields

$$\widetilde{mc}_t^s + \widetilde{A}_t = \bar{\alpha}_s\left(\frac{r^k}{mc^s A}\right)^{1-\varrho}\tilde{r}_t^k + (1-\bar{\alpha}_s)\left(\frac{w^{zs}}{mc^s A}\right)^{1-\varrho}\widetilde{w}_t^{zs}.$$

It can be expressed in the following way.

$$\begin{aligned}\widetilde{mc}_t^s + \widetilde{A}_t &= \frac{r^k}{mc^s\left(y^s+\bar{f}_s\right)}\left\{\bar{\alpha}_s\left(\frac{mc^s}{r^k}\right)^{\varrho}\frac{y^s+\bar{f}_s}{A^{1-\varrho}}\right\}\tilde{r}_t^k \\ &+ \frac{w^{zs}}{mc^s\left(y^s+\bar{f}_s\right)}\left\{(1-\bar{\alpha}_s)\left(\frac{mc^s}{w^{zs}}\right)^{\varrho}\frac{y^s+\bar{f}_s}{A^{1-\varrho}}\right\}\widetilde{w}_t^{zs}.\end{aligned}$$

Substitute formula (118) and (119) for the expressions in curly brackets,

$$\widetilde{mc}_t^s + \widetilde{A}_t = \frac{r^k k^s}{mc^s\left(y^s+\bar{f}_s\right)}\tilde{r}_t^k + \frac{w^{zs}z^s}{mc^s\left(y^s+\bar{f}_s\right)}\widetilde{w}_t^{zs}.$$

Let us define

$$\alpha_s = \frac{r^k k^s}{mc^s\left(y^s+\bar{f}_s\right)}.$$

Homogeneity of the marginal cost function implies that

$$1-\alpha_s = \frac{w^{zs}z^s}{mc^s\left(y^s+\bar{f}_s\right)}.$$

$$\widetilde{mc}_t^s = \alpha_s\tilde{r}_t^k + (1-\alpha_s)\,\widetilde{w}_t^{zs} - \widetilde{A}_t. \tag{185}$$

Let us log-linearize (118),

$$\tilde{k}_t^s + \tilde{u}_t = \varrho\left(\widetilde{mc}_t^s - \tilde{r}_t^k\right) + \frac{y^s}{y^s+\bar{f}_s}\tilde{y}_t^s - (1-\varrho)\widetilde{A}_t.$$

where it was used that $\widetilde{DP}_t^s = 0$. It is a corollary of equation (114), since it implies $\widetilde{P}_t = \int_0^1 \widetilde{P}_t(i)\,di$. Substitute (185)

$$\tilde{k}_t^s + \tilde{u}_t = \varrho(1-\alpha_d)\left(\widetilde{w}_t^{zs} - \tilde{r}_t^k\right) + \frac{\tilde{y}_t^s}{1+f_s} - \widetilde{A}_t,$$

where $f_s = \bar{f}_s / y_s$. According to equation (142) $r_t^k = \Psi'(u_t)$. Log-linearizing this formula yields $r^k \tilde{r}_t^k = \Psi''(1) u \tilde{u}_t$. Since $r^k = \Psi'(1) u$,

$$\tilde{r}_t^k = \frac{\Psi''(1)}{\Psi'(1)} \tilde{u}_t = \frac{1}{\psi} \tilde{u}_t.$$

Hence,

$$\tilde{k}_t^s = \varrho(1-\alpha_s)\left(\widetilde{w}_t^{zs} - \tilde{r}_t^k\right) - \psi \tilde{r}_t^k + \frac{\tilde{y}_t^s}{1+f_s} - \widetilde{A}_t,$$

which is identical to the log-linearized demand equations of (170) in *Section 3.2.7.* One can show the same way that equation (119) implies that

$$\tilde{z}_t^s = \varrho \alpha_d \left(\tilde{r}_t^k - \widetilde{w}_t^{zs}\right) - \psi \tilde{r}_t^k + \frac{\tilde{y}_t^s}{1+f_s} - \widetilde{A}_t.$$

The cost minimization problem of producers of z^s is the following.

$$\mathsf{K}_s\left(W_t, e_t P_t^{m*}, z_t^s\right) = \min_{l_t^s, m_t^s} W_t l^s + e_t P_t^{m*},$$

subject to

$$\left(z_t^s + \mathsf{k}_t^s\right)^{\frac{\varrho_z - 1}{\varrho_z}} = \bar{a}_s^{\frac{1}{\varrho_z}} \left(m_t^s\right)^{\frac{\varrho_z - 1}{\varrho_z}} + (1-\bar{a}_s)^{\frac{1}{\varrho_z}} \left(l_t^s\right)^{\frac{\varrho_z - 1}{\varrho_z}},$$

where $\mathsf{k}_t^s = z_t^s \Phi_{zs}\left(z_t^s\right)$. The Lagrangian is

$$W_t l^s + e_t P_t^{m*} + \varsigma \left[\left(z_t^s + \mathsf{k}_t^s\right)^{\frac{\varrho_z - 1}{\varrho_z}} - \bar{a}_s^{\frac{1}{\varrho_z}} \left(m_t^s\right)^{\frac{\varrho_z - 1}{\varrho_z}} - (1-\bar{a}_s)^{\frac{1}{\varrho_z}} \left(l_t^s\right)^{\frac{\varrho_z - 1}{\varrho_z}}\right].$$

The first-order conditions are

$$\begin{aligned} W_t l_t^s &= \varsigma \bar{a}_s^{\frac{1}{\varrho_z}} \frac{\varrho_z - 1}{\varrho_z} \left(l_t^s\right)^{\frac{\varrho_z - 1}{\varrho_z}}, \\ e_t P^{m*} m_t^s &= \varsigma (1-\bar{a}_s)^{\frac{1}{\varrho_z}} \frac{\varrho_z - 1}{\varrho_z} \left(m_t^s\right)^{\frac{\varrho_z - 1}{\varrho_z}}. \end{aligned}$$

This implies

$$\begin{aligned} \mathsf{K}_s\left(W_t, e_t P_t^{m*}, z_t^s\right) &= W_t l_t^s + e_t P^{m*} m_t^s = \varsigma \frac{\varrho_z - 1}{\varrho_z} \left(\bar{a}_s^{\frac{1}{\varrho_z}} \left(m_t^s\right)^{\frac{\varrho_z - 1}{\varrho_z}} + (1-\bar{a}_s)^{\frac{1}{\varrho_z}} \left(l_t^s\right)^{\frac{\varrho_z - 1}{\varrho_z}}\right) \\ &= \varsigma \frac{\varrho_z - 1}{\varrho_z} \left(z_t^s + \mathsf{k}_t^s\right)^{\frac{\varrho_z - 1}{\varrho_z}}. \end{aligned}$$

Hence the Lagrange-multiplier is

$$\varsigma = \mathsf{K}_s(\cdot) \frac{\varrho_z - 1}{\varrho_z} \left(z_t^s + \mathsf{k}_t^s\right)^{\frac{1 - \varrho_z}{\varrho_z}}.$$

Substituting it back to the first-order conditions results in

$$\begin{aligned} l_t^s &= \bar{a}_s \left(\frac{\mathsf{K}(\cdot)}{W_t}\right)^{\varrho_z} \left(z_t^s + \mathsf{k}_t^s\right)^{1-\varrho_z}, \qquad (186) \\ m_t^s &= (1-\bar{a}_s) \left(\frac{\mathsf{K}(\cdot)}{e_t P_t^{m*}}\right)^{\varrho_z} \left(z_t^s + \mathsf{k}_t^s\right)^{1-\varrho_z}. \qquad (187) \end{aligned}$$

Substituting the above expression into the constraint of the minimization problem and rearranging it yields the closed form solution of the cost function,

$$\mathsf{K}_s\left(W_t, e_t P_t^{m*}, z_t^s\right) = \left[\bar{a}_s W_t^{1-\varrho_z} + (1-\bar{a}_s)\left(e_t P_t^{m*}\right)^{1-\varrho_z}\right]^{\frac{1}{1-\varrho_z}} \left(z_t^s + \mathsf{k}_t^s\right).$$

The accompanying marginal cost function is

$$W_t^{zs} = \frac{\partial \mathsf{K}_s(\cdot)}{\partial z_t^s} = \left[\bar{a}_s W_t^{1-\varrho_z} + (1-\bar{a}_s)\left(e_t P_t^{m*}\right)^{1-\varrho_z}\right]^{\frac{1}{1-\varrho_z}} \left(1 + \frac{\partial \mathsf{k}_t^s}{\partial z_t^s}\right),$$

which is equivalent with equation equation (121) in *Section 3.2.1.* Substituting K_s into equation (186) and (187) yields the input demand functions,

$$\begin{aligned} l_t^s &= \bar{a}_s \left(\frac{\left[\bar{a}_s w_t^{1-\varrho_z} + (1-\bar{a}_s)\left(q_t P_t^{m*}\right)^{1-\varrho_z}\right]^{\frac{1}{1-\varrho_z}}}{W_t}\right)^{\varrho_z} \left(z_t^s + \mathsf{k}_t^s\right), \\ m_t^s &= (1-\bar{a}_s) \left(\frac{\left[\bar{a}_s w_t^{1-\varrho_z} + (1-\bar{a}_s)\left(q_t P_t^{m*}\right)^{1-\varrho_z}\right]^{\frac{1}{1-\varrho_z}}}{e_t P_t^{m*}}\right)^{\varrho_z} \left(z_t^s + \mathsf{k}_t^s\right), \end{aligned}$$

recall that $w_t = W_t/P_t$ and $q_t = P_t/e_t$. The above two expressions are identical to equations (122) and (123) in *Section 3.2.1.*

Define $w^{zs} = W_t^{zs}/P_t$. Then equation (121) implies that

$$w_t^{zs} = \left[\bar{a}_s w_t^{1-\varrho_z} + (1-\bar{a}_s)\left(q_t P_t^{m*}\right)^{1-\varrho_z}\right]^{\frac{1}{1-\varrho_z}} \left[1 + \Phi_{zs}\left(z_t^s\right) + z_t^s \Phi'_{zs}\left(z_t^s\right)\right].$$

As above, one can show that

$$\widetilde{w}_t^{zs} = a^s \widetilde{w}_t + (1-a_s)\left(\tilde{q}_t + \widetilde{P}_t^{m*}\right) + \tilde{\mathsf{z}}_t^s,$$

where

$$a_s = \frac{w l^s}{w^{zs} z^s},$$

and

$$\mathsf{z}_t^s = 1 + \Phi_{zs}\left(z^s\right) + z^s \Phi'_{zs}\left(z^s\right).$$

Log-linearizing z_t^s yields

$$\mathsf{z}^s \tilde{\mathsf{z}}_t^s = \left[2\Phi'_z\left(z^s\right) + z^s \Phi''_{zs}\left(z^s\right)\right] z_t^s \tilde{z}_t = \left(z^s\right)^2 \Phi''_{zs}\left(z^s\right) \tilde{z}_t,$$

where the second equation is a consequence of the assumptions $\Phi_{zs}\left(z^s\right) = \Phi'_{zs}\left(z^s\right) = 0$. They also imply that $\mathsf{z}^s = 1$. Hence,

$$\tilde{\mathsf{z}}_t^s = \left(z^s\right)^2 \Phi''_z\left(z^s\right) \tilde{z}_t^s = \phi_z \tilde{z}_t^s.$$

As a consequence,

$$\widetilde{w}_t^{zs} = a^s \widetilde{w}_t + (1-a_s)\left(\tilde{q}_t + \widetilde{P}_t^{m*}\right) + \phi_z \tilde{z}_t^s, \tag{188}$$

$$\widetilde{\overline{w}}_t^{zs} = a^s \widetilde{w}_t + (1-a_s)\left(\tilde{q}_t + \widetilde{P}_t^{m*}\right). \tag{189}$$

Equations (122) and (123) imply that

$$\begin{aligned}
\tilde{l}_t^s &= \varrho_z \left(\widetilde{\overline{w}}_t^{zs} - \widetilde{w}_t\right) + \tilde{\mathsf{y}}_t^s, \\
\widetilde{m}_t^s &= \varrho_z \left(\widetilde{\overline{w}}_t^{zs} - \tilde{q}_t - \widetilde{P}_t^{m*}\right) + \tilde{\mathsf{y}}_t^s,
\end{aligned}$$

where

$$\mathsf{y}_t^s = z_t^s + z^s \Phi_{zs}\left(z_t^s\right).$$

Substituting formula (189) into the above expressions yields

$$\begin{aligned}
\tilde{l}_t^s &= \varrho_z (1-a_s)\left(\tilde{q}_t + \widetilde{P}_t^{m*} - \widetilde{w}_t\right) + \tilde{\mathsf{y}}_t^s, \\
\widetilde{m}_t^s &= \varrho_z a_s \left(\widetilde{w}_t - \tilde{q}_t - \widetilde{P}_t^{m*}\right) + \tilde{\mathsf{y}}_t^s.
\end{aligned}$$

These equations are equivalent with formulas (171) and (172) in *Section 3.2.7*, since

$$\mathsf{y}^s \tilde{\mathsf{y}}_t^s = z^s \tilde{z}_t^s + \left[\Phi_{zs}\left(z^s\right) + z^s \Phi'_{zs}\left(z^s\right)\right] z_t^s \tilde{z}_t = z^s \tilde{z}_t^s,$$

and $\mathsf{y}^s = z^s$.

B.1.2 Price setting

Equations (125) and (126) imply that

$$\begin{aligned}
\mathcal{Z}_t^1 &= \Lambda_t^o y_t^d mc_t^d + \sum_{T=t+1}^{\infty} \left(\beta\gamma_d\right)^{T-t} \mathrm{E}_t \left[\Lambda_T^o y_T^d mc_T^d \left(\frac{P_T}{P_t \Pi_t^I}\right)^{\theta}\right], \\
\mathcal{Z}_t^2 &= \tau_t^d \Lambda_t^o y_t^d + \sum_{T=t+1}^{\infty} \left(\beta\gamma_d\right)^{T-t} \mathrm{E}_t \left[\tau_T^d \Lambda_T^o y_T^d \left(\frac{P_T}{P_t \Pi_t^I}\right)^{\theta-1}\right].
\end{aligned}$$

With some manipulations it is easy to show that $\mathcal{Z}_t^1$ can be expressed in the recursive way of formula (127),

$$\begin{aligned}
\mathcal{Z}_t^1 &= \Lambda_t^o y_t^d mc_t^d + \beta\gamma_d \mathrm{E}_t \left[\left(\frac{\Pi_{t+1}}{\Pi_t^I}\right)^{\theta} \sum_{T=t+1}^{\infty} \left(\beta\gamma_d\right)^{T-t-1} \Lambda_T^o y_T^d mc_T^d \left(\frac{P_T}{P_{t+1}\Pi_{t+1}^I}\right)^{\theta}\right] \\
&= \Lambda_t^o y_t^d mc_t^d + \beta\gamma_d \mathrm{E}_t \left[\left(\frac{\Pi_{t+1}}{\Pi_t^I}\right)^{\theta} \mathcal{Z}_{t+1}^1\right],
\end{aligned}$$

Similarly, one can show that $\mathcal{Z}_t^2$ can be expressed as in equation (128).

The log-linear version of equation (129) is

$$\widetilde{\mathcal{P}}_t = \frac{\gamma_d}{1-\gamma_d}\breve{\pi}_t, \tag{190}$$

where $\breve{\pi}_t = \pi_t - \bar{\pi}_t - \vartheta_d\left(\pi_{t-1} - \bar{\pi}_{t-1}\right)$, $\pi_t = \widetilde{P}_t - \widetilde{P}_{t-1}$ and $\bar{\pi}_t = \tilde{\bar{\Pi}}_t$. Equation (126) implies that

$$\widetilde{\mathcal{P}}_t = \widetilde{\mathcal{Z}}^1_t - \widetilde{\mathcal{Z}}^2_t. \tag{191}$$

The log-linearization of formulas (127) and (128) results in

$$\begin{aligned}
\widetilde{\mathcal{Z}}^1_t &= \frac{\Lambda^o y^d mc^d}{\mathcal{Z}^1}\left(\widetilde{\Lambda}^o_t + \tilde{y}^d_t + \widetilde{mc}^d_t\right) + \beta\gamma \mathrm{E}_t\left[\theta\breve{\pi}_{t+1} + \tilde{\mathcal{Z}}^1_{t+1}\right], &(192)\\
\widetilde{\mathcal{Z}}^2_t &= \frac{\Lambda^o y^d \tau^d}{\mathcal{Z}^2}\left(\widetilde{\Lambda}^o_t + \tilde{y}^d + \tilde{\tau}^d_t\right) + \beta\gamma \mathrm{E}_t\left[(\theta-1)\breve{\pi}_{t+1} + \tilde{\mathcal{Z}}^2_{t+1}\right], &(193)
\end{aligned}$$

where it is used that $\Pi/\Pi^I = 1$. Observe that

$$\frac{\Lambda^o y^d mc^d}{\mathcal{Z}^1} = \frac{\Lambda^o y^d \tau^d}{\mathcal{Z}^2} = (1-\beta\gamma_d),$$

hence combining expressions (191), (192) and (193) yields

$$\widetilde{\mathcal{P}}_t = (1-\beta\gamma_d)\left(\widetilde{mc}^d_t - \tilde{\tau}^d_t\right) + \beta\gamma \mathrm{E}_t\left[\widetilde{\mathcal{P}}_{t+1}\right] + \beta\gamma \mathrm{E}_t\left[\breve{\pi}_{t+1}\right].$$

Formula (190) implies that

$$\breve{\pi}_t = \beta \mathrm{E}_t[\breve{\pi}_{t+1}] + \xi_d\widetilde{mc}^d_t + \tilde{\upsilon}_t, \tag{194}$$

where

$$\xi_d = \frac{(1-\beta\gamma_d)(1-\gamma_d)}{\gamma_d} \text{ and } \tilde{\upsilon}_t = -\xi_d\tilde{\tau}^d_t.$$

Formulas (185) and (188) imply that

$$\begin{aligned}
\widetilde{mc}^d_t &= \alpha_d\tilde{r}^k_t + (1-\alpha_d)a_d\widetilde{w}_t + (1-\alpha_d)(1-a_d)\left(\tilde{q}_t + \widetilde{P}^{m*}_t\right)\\
&+ (1-\alpha_d)\phi_z\tilde{z}^d_t - \widetilde{A}_t,
\end{aligned}$$

hence expression (194) is equivalent with the Phillips-curve equation (173) in *Section 3.2.7.*

As above, one can prove that the first-order condition of price setting in the export sector can be represented by expressions (131), (132) and (133). Using the log-linear versions of the previous formulas and that of equation (134), it is easy to show that price setting behavior of the export sector can be described by

$$\breve{\pi}^{x*}_t = \beta \mathrm{E}_t[\breve{\pi}^{x*}_{t+1}] + \xi_x\widetilde{mc}^{x*}_t + \tilde{\upsilon}^x_t, \tag{195}$$

where where $\breve{\pi}^{x*}_t = \pi^{x*}_t - \bar{\pi}^{x*}_t - \vartheta_x\left(\pi^{x*}_{t-1} - \bar{\pi}^{x*}_{t-1}\right)$, $\pi^{x*}_t = \widetilde{P}^{x*}_t - \widetilde{P}^{x*}_{t-1}$, $\bar{\pi}^{x*}_t = \tilde{\bar{\Pi}}^{x*}_t$,

$$\xi_x = \frac{(1-\beta\gamma_x)(1-\gamma_x)}{\gamma_x} \text{ and } \tilde{\upsilon}^x_t = -\xi_x\tilde{\tau}^x_t.$$

The log-linear version of equation (130) is

$$\widetilde{mc}_t^{x*} = \widetilde{mc}_t^x + \widetilde{P}_t - \tilde{e}_t - \widetilde{P}_t^{x*} = \widetilde{mc}_t^x - \tilde{q}_t - \widetilde{P}_t^{x*}.$$

Applying formulas (185) and (188) yields

$$\begin{aligned}\widetilde{mc}_t^x &= \alpha_x \tilde{r}_t^k + (1-\alpha_x) a_x \widetilde{w}_t + (1-\alpha_x)(1-a_x)\widetilde{P}_t^{m*} \\ &- [\alpha_x + (1-\alpha_x)a_x]\, \tilde{q}_t + (1-\alpha_x)\phi_x \tilde{z}_t^x - \widetilde{P}_t^{x*} - \widetilde{A}_t.\end{aligned}$$

Hence equation (195) is equivalent with formula (174) in *Section 3.2.7*.

B.1.3 Optimizing households

The representative household maximizes the objective function (135) subject to the budget constraint (136) the investments equation (137), with respect to c_t, B_t, k_{t+1}, I_t and u_t. The corresponding Lagrangian is given by

$$\begin{aligned}&\sum_{t=0}^{\infty} \int \text{prob}_t(s_t|s_0)\beta^t \eta_t^c \left\{U(c_t^o(j) - hc_{t-1}^o) - \eta_t^l V(l_t(j))\right\} ds_t \\ &+ \sum_{t=0}^{\infty} \beta\lambda_t \left\{P_t c_t^o(j) + P_t I_t(j) + B_t()j(1+i_t)^{-1} + P_t^w X_t^w()j\right. \\ &\left. - B_{t-1}(j) - \chi_t X_{t-1}^w(j) - W_t(j)l_t(j) - P_t r_t^k u_t(j)k_t(j) - \Psi(u_t(j)) - Div_t\right\}, \\ &+ \sum_{t=0}^{\infty} \beta\lambda_t Q_t \left\{k_{t+1}(j) - (1-\delta)k_t(j) + \left[1 - \Phi_I\left(\frac{\eta_t^I I_t(j)}{I_{t-1}(j)}\right)\right] I_t(j)\right\},\end{aligned}$$

where λ_t and Q_t are state dependent Lagrange multipliers and s_t denotes the state of the world at date t and $\text{prob}_t(\cdot)$ is the appropriate conditional density function.

Due to the existence of asset X_t^w the wage incomes of all households are the same. As a consequence, all households choose the same solutions. Hence, index j is drooped from subsequent notations.

The first order condition with respect to c_t is

$$P_t\lambda_t = \text{prob}(s_t|s_0)\Lambda_t^o = \text{prob}(s_t|s_0)\eta_t^c (c_t^o - hc_{t-1}^o)^{-\sigma}. \tag{196}$$

The first order condition with respect to B_t takes the form of

$$\beta\lambda_t = (1+i_t)\beta^{t+1}\lambda_{t+1}, \tag{197}$$

where $(1+i_t) = 1/P_t^B$. Combining equations (196) and (197) yields

$$\frac{\Lambda_t^o}{P_t} = \beta(1+i_t)\int \text{prob}(s_{t+1}|s_t)\frac{\Lambda_{t+1}^o}{P_{t+1}}\, ds_{t+1} = \beta \mathrm{E}_t\left[\frac{\Lambda_{t+1}^o}{P_{t+1}}\right].$$

where it is used that

$$\text{prob}(s_{t+1}|s_t) = \frac{\text{prob}_{t+1}(s_{t+1}|s_0)}{\text{prob}_t(s_t|s_0)}.$$

The above equation can be expressed as

$$1 = (1 + i_t)\mathrm{E}_t\left[D_{t+1,t}\right], \tag{198}$$

where

$$D_{t+j,1} = \beta^j \frac{\Lambda^o_{t+j} P_t}{\Lambda^o_t P_{t+j}}$$

is the stochastic discount factor.

The first-order condition with respect to k_{t+1} is given by the following equation.

$$\beta^t Q_t \lambda_t = \beta^{t+1}\lambda_{t+1}\left[Q_{t+1}(1-\delta) + r^k_{t+1} u_{t+1} - \Psi\left(u_{t+1}\right)\right].$$

Substitute equation (196) into the above formula.

$$Q_t = \beta \int \mathrm{prob}(s_{t+1}|s_t)\frac{\Lambda^o_{t+1}}{\Lambda^o_{t+1}}\left[Q_{t+1}(1-\delta) + r^k_{t+1}u_{t+1} - \Psi\left(u_{t+1}\right)\right] ds_{t+1}.$$

$$Q_t = \beta \mathrm{E}_t\left[D_{t+1,t}\left(Q_{t+1}(1-\delta) + r^k_{t+1} z_{t+1} - \Psi\left(u_{t+1}\right)\right)\right]. \tag{199}$$

Equation (199) is equivalent with expression (141) in *Section 3.2.2*.

The first order condition with respect to I_t yields the following formula.

$$\begin{aligned} 0 &= \beta^t \lambda^t Q_t\left[1 - \Phi_I\left(\frac{\eta^I_t I_t}{I_{t-1}}\right) - \Phi'_I\left(\frac{\eta^I_t I_t}{I_{t-1}}\right)\frac{\eta^I_t I_t}{I_{t-1}}\right] - \beta^t\lambda_t \\ &+ \beta^{t+1}\lambda_{t+1}Q_{t+1}\Phi'_I\left(\frac{\eta^I_{t+1}I_{t+1}}{I_t}\right)\frac{\eta^I_{t+1}I^2_{t+1}}{I^2_t}. \end{aligned}$$

One can show, as previously, that it implies the following expression.

$$\begin{gathered} Q_t\left[1 - \Phi_I\left(\frac{\eta^I_t I_t}{I_{t-1}}\right) - \Phi'_I\left(\frac{\eta^I_t I_t}{I_{t-1}}\right)\frac{\eta^I_t I_t}{I_{t-1}}\right] = \\ 1 - \beta\mathrm{E}_t\left[D_{t+1,1}Q_{t+1}\Phi'_I\left(\frac{\eta^I_{t+1}I_{t+1}}{I_t}\right)\frac{\eta^I_{t+1}I^2_{t+1}}{I^2_t}\right]. \end{gathered} \tag{200}$$

The above equation is equivalent with expression (140) in *Section 3.2.2*.

Finally, the first order condition with respect to u_t is given by

$$r^k_t = \Psi'(u_t). \tag{201}$$

This expression is the same as formula (142) in *Section 3.2.2*.

Log-linearization of formulas (198) and (201) is straightforward. Let us log-linearize expression (200). First, observe the steady-state form of the formula.

$$Q\left[1 - \Phi_I(1) - \Phi'_I(1)\right] = 1 - \beta Q \Phi'_I(1).$$

Since, by assumption, $\Phi_I(1) = \Phi'_I(1) = 0$, the previous equation implies that $Q = 1$. Define

$$\mu(\mathsf{x}) = \left.\frac{d\Phi'_I\left(\eta^I_t I_t I^{-1}_{t-1}\right)\eta^I_t I_t I^{-1}_{t-1}}{d\mathsf{x}}\right|_{(\eta^I_t=1, I_t=I, I_{t-1}=I)},$$

where $\mathsf{x} = \eta_t^I, I_t, I_{t-1}$, and

$$\mu^+(\mathsf{y}) = \left. \frac{d\Phi_I'\left(\eta_{t+1}^I I_{t+1} I_t^{-1}\right)\eta_{t+1}^I I_{t+1}^2 I_t^{-2}}{d\mathsf{y}} \right|_{(\eta_{t+1}^I=1, I_{t+1}=I, I_t=I)},$$

where $\mathsf{y} = \eta_{t+1}^I, I_{t+1}, I_t$. Since $Q = 1$ and $\Phi_I(1) = \Phi_I'(1) = 0$ the log-linear version of equation (200) takes the form of

$$\begin{aligned}&\widetilde{Q}_t - \mu(I_t)I\tilde{I}_t - \mu(I_{t-1})I\tilde{I}_{t-1} - \mu\left(\eta_t^I\right)\tilde{\eta}_t^I = \\ &-\beta\mu^+(I_{t+1})I\mathrm{E}_t\left[\tilde{I}_{t+1}\right] - \beta\mu^+(I_t)I\tilde{I}_t - \beta\mu^+\left(\eta_{t+1}^I\right)\mathrm{E}_t\left[\tilde{\eta}_{t+1}^I\right].\end{aligned}$$

Observe that

$$\mu(I_t) = \frac{\Phi_I''(1)}{I}, \qquad \mu(I_{t-1}) = -\frac{\Phi_I''(1)}{I}, \qquad \mu\left(\eta_t^I\right) = \Phi_I''(1),$$

furthermore,

$$\mu^+(I_{t+1}) = \frac{\Phi_I''(1)}{I}, \qquad \mu^+(I_t) = -\frac{\Phi_I''(1)}{I}, \qquad \mu^+\left(\eta_{t+1}^I\right) = \Phi_I''(1).$$

As a consequence,

$$\Phi_I''(1)(1+\beta)\tilde{I}_t = \Phi_I''(1)\left\{\beta\mathrm{E}_t\left[\tilde{I}_{t+1}\right] + \tilde{I}_{t-1} - \tilde{\eta}_t^I + \beta\mathrm{E}_t\left[\tilde{\eta}_{t+1}^I\right]\right\} + \widetilde{Q}_t.$$

The above expression is equivalent with equation (165) in *Section 3.2.7.*

The log-linear version of equation (199) is given by

$$\widetilde{Q}_t - \mathrm{E}_t\left[\tilde{D}_{t+1,1}\right] = \frac{Q(1-\delta)\mathrm{E}_t\left[\widetilde{Q}_{t+1}\right] + r^k u\mathrm{E}_t\left[\tilde{r}_{t+1}^k + \tilde{u}_{t+1}\right] - \Psi'(1)\mathrm{E}_t\left[u_{t+1}\right]}{Q(1-\delta) + r^k u - \Psi(1)}.$$

Since $Q = 1$, $u = 1$, $\Psi(1) = 0$ and equation (201) implies that $r^k = \Psi'(1)$, it takes the form of

$$\widetilde{Q}_t - \mathrm{E}_t\left[\tilde{D}_{t+1,1}\right] = \frac{1-\delta}{1-\delta+r^k}\mathrm{E}_t\left[\widetilde{Q}_{t+1}\right] + \frac{r^k}{1-\delta+r^k}\mathrm{E}_t\left[\tilde{r}_{t+1}^k\right].$$

The log-linearized version of equation (198) implies that

$$\tilde{\imath}_t - \pi_{t+1} = \mathrm{E}_t\left[\tilde{D}_{t+1,t}\right],$$

hence

$$\tilde{\imath}_t - \mathrm{E}_t\left[\pi_{t+1}\right] = \frac{1-\delta}{1-\delta+r^k}\mathrm{E}_t\left[\widetilde{Q}_{t+1}\right] - \widetilde{Q}_t + \frac{r^k}{1-\delta+r^k}\mathrm{E}_t\left[\tilde{r}_{t+1}^k\right].$$

The above equation is equivalent with formula (164) in *Section 3.2.7.*

B.1.4 Wage setting

First order conditions (146) and (147) imply that

$$\sum_{T=t}^{\infty}(\gamma_w\beta)^{T-t}\mathrm{E}_t\left[l_T\left(\frac{W_T}{W_t(j)\Pi_{T,t}^{Iw}}\right)^{\theta_w}\tau_T^w\frac{\Lambda_T^l}{P_T}\Pi_{T,t}^{Iw}\right]=$$
$$\frac{\theta_w}{\theta_w-1}\sum_{T=t}^{\infty}(\gamma_w\beta)^{T-t}\mathrm{E}_t\left[l_T\left(\frac{W_T}{W_t(j)\Pi_{T,t}^{Iw}}\right)^{\theta_w}\eta_T^c\eta_T^l\frac{l_T(j)^{\varphi}}{W_t(j)}\right],$$

where $\Lambda_T^l=\left(\bar{\omega}^o\lambda_T^o+\bar{\omega}^{no}\lambda_T^{no}\right)/\left(\bar{\omega}^o+\bar{\omega}^{no}\right)$ Substituting the demand equation (145) for $l_T(j)$ results in

$$\sum_{T=t}^{\infty}(\gamma_w\beta)^{T-t}\mathrm{E}_t\left[l_T\left(\frac{W_T}{W_t(j)\Pi_{T,t}^{Iw}}\right)^{\theta_w}\frac{\Pi_{T,t}^{Iw}}{W_T}\tau_T^w\Lambda_T^l w_T\right]=$$
$$\frac{\theta_w}{\theta_w-1}\sum_{T=t}^{\infty}(\gamma_w\beta)^{T-t}\mathrm{E}_t\left[l_T\left(\frac{W_T}{W_t(j)\Pi_{T,t}^{Iw}}\right)^{\theta_w}\frac{\Pi_{T,t}^{Iw}}{W_T}\eta_T^c\eta_T^l\frac{l_T^{\varphi}W_T^{\iota}}{\left(W_t(j)\Pi_{T,t}^{Iw}\right)^{\iota}}\right],$$

where $\iota=\theta_w\varphi+1$. After some manipulations one can get

$$\sum_{T=t}^{\infty}(\gamma_w\beta)^{T-t}\mathrm{E}_t\left[l_T\left(\frac{W_T}{W_t\Pi_{T,t}^{Iw}}\right)^{\theta_w+\iota-1}\tau_T^w\Lambda_T^l w_T\left(\frac{W_t(j)}{W_t}\right)^{\iota}\left(\frac{W_t\Pi_{T,t}^{Iw}}{W_T}\right)^{-\iota}\right]=$$
$$\frac{\theta_w}{\theta_w-1}\sum_{T=t}^{\infty}(\gamma_w\beta)^{T-t}\mathrm{E}_t\left[\left(\frac{W_T}{W_t\Pi_{T,t}^{Iw}}\right)^{\theta_w+\iota-1}\eta_T^c\eta_T^l l_T^{\varphi+1}\right],$$

Rearranging the above expression yields

$$\left(\frac{W_t(j)}{W_t}\right)^{\iota}=\frac{\theta_w}{\theta_w-1}\frac{\sum_{T=t}^{\infty}(\gamma_w\beta)^{T-t}\mathrm{E}_t\left[\left(\frac{W_T}{W_t\Pi_{T,t}^{Iw}}\right)^{\theta_w+\iota-1}\eta_T^c\eta_T^l l_T^{\varphi+1}\right]}{\sum_{T=t}^{\infty}(\gamma_w\beta)^{T-t}\mathrm{E}_t\left[l_T\left(\frac{W_T}{W_t\Pi_{T,t}^{Iw}}\right)^{\theta_w-1}\tau_T^w\Lambda_T^l w_T\right]}. \quad (202)$$

This implies that all unions choose the same $W_t(j)=W^{\star}$. Denote $\mathcal{W}_t=W_t^{\star}/W_t$, then equation (202) implies formulas (148), (146) and (147) in *Section 3.2.2*.

Log-linearization of equations (148) and (151) results in

$$\begin{aligned}\widetilde{\mathcal{W}}_t &= \frac{\gamma_w}{1-\gamma_w}\breve{\pi}_t^w,\\ \iota\widetilde{\mathcal{W}}_t &= \widetilde{\mathcal{Z}}_t^{w1}-\widetilde{\mathcal{Z}}_t^{w2},\end{aligned}$$

where $\breve{\pi}^w_t = \widetilde{w}_t - \widetilde{w}_{t-1} + \pi_t - \bar{\pi}_t - \vartheta_w(\widetilde{w}_{t-1} - \widetilde{w}_{t-2} + \pi_{t-1} - \bar{\pi}_{t-1})$. Expressions (146) and (147) imply that

$$\begin{aligned}
\widetilde{\mathcal{Z}}^{w1}_t - \widetilde{\mathcal{Z}}^{w2}_t &= (1-\beta\gamma_w)\left[\varphi\tilde{l}_t + \frac{\sigma}{1-h}\left(\tilde{c}^l_t - h\tilde{c}^l_{t-1}\right) + \tilde{\eta}^l_t - \tilde{\tau}^w_t\right] \\
&+ \beta\gamma_w \mathrm{E}_t\left[\widetilde{\mathcal{Z}}^{w1}_{t+1} - \widetilde{\mathcal{Z}}^{w2}_{t+1}\right] + \iota\beta\gamma_w \mathrm{E}_t\left[\breve{\pi}^w_{t+1}\right],
\end{aligned}$$

where

$$\tilde{c}^l_t = \frac{\bar{\omega}^o\left(c^o\right)^{-\sigma}\tilde{c}^o_t + \bar{\omega}^{no}\left(c^{no}\right)^{-\sigma}\tilde{c}^{no}_t}{\bar{\omega}^o\left(c^o\right)^{-\sigma} + \bar{\omega}^{no}\left(c^{no}\right)^{-\sigma}},$$

and it was used that $\Pi^w/\Pi^{Iw} = 1$ and

$$\frac{l^{\varphi+1}}{\mathcal{Z}^{w1}} = \frac{\Lambda^a w l}{\mathcal{Z}^{w2}} = (1-\beta\gamma_w).$$

Combining the above expressions yields equation (175) in *Section 3.2.7.*

B.2 The steady state

Variables without time indices represent their steady-state values.

The steady state of the model is calculated in two stages. First, given the values of $\beta = 0.99$, $\delta = 0.025$, $\theta = \theta^d = \theta^x = 6$, $p^{m*} = P^{m*}/P = 1$, $e = 1$, $\mathsf{S}^{m^d}_{gdp^d} = 0.702$ (the share of imports in value-added in sector d), $\mathsf{S}^{m^x}_{gdp^x} = 1.237$ (the share of imports in value-added in sector x), $\mathsf{S}^I_y = 0.112$ (the share of investments in total output), $\bar{f}_d = \bar{f}_x = 0.2$ and then r^k, $\bar{\alpha}_d$, $\bar{\alpha}_x$, $\bar{a}_d$, $\bar{a}_x$,$w = W/P$, $\kappa = x/y^d$ are calculated.

The steady-state value of the rental rate of capital is given by. $r^k = \beta^{-1} - 1 + \delta$.

Formula (121) implies that

$$\begin{aligned}
w^{zd} &= \left[\bar{a}_d w^{1-\varrho_z} + (1-\bar{a}_d)\left(p^{m*}\right)^{1-\varrho_z}\right]^{\frac{1}{1-\varrho_z}}, \\
w^{zx} &= \left[\bar{a}_x w^{1-\varrho_z} + (1-\bar{a}_x)\left(p^{m*}\right)^{1-\varrho_z}\right]^{\frac{1}{1-\varrho_z}},
\end{aligned}$$

where $w^{zd} = W^{zd}/P$, $w^{zx} = W^{zx}/P$.

The steady-state form of formula (117) is

$$\begin{aligned}
mc^d &= \left[\bar{\alpha}_d\left(r^k\right)^{1-\varrho} + (1-\bar{\alpha}_d)\left(w^{zs}\right)^{1-\varrho}\right]^{\frac{1}{1-\varrho}}, \\
mc^x &= \left[\bar{\alpha}_x\left(r^k\right)^{1-\varrho} + (1-\bar{\alpha}_x)\left(w^{zs}\right)^{1-\varrho}\right]^{\frac{1}{1-\varrho}},
\end{aligned}$$

where $mc^d = MC^d/P$, $mc^x = MC^x/P$, $r^k = R^k/P$.

Demand equations (118), (119), and (123) imply that

$$\begin{aligned}
k^d &= \bar{\alpha}_d \left(\frac{mc^d}{r^k}\right)^{\varrho} y^d \left(1+f_d\right), \\
k^x &= \bar{\alpha}_x \left(\frac{mc^x}{r^k}\right)^{\varrho} \kappa y^d \left(1+f_x\right), \\
z^d &= \left(1-\bar{\alpha}_d\right) \left(\frac{mc^d}{w^d}\right)^{\varrho} y^d \left(1+f_d\right), \\
z^x &= \left(1-\bar{\alpha}_x\right) \left(\frac{mc^x}{w^x}\right)^{\varrho} \kappa y^d \left(1+f_x\right), \\
m^d &= \left(1-\bar{a}_d\right) \left(\frac{w_t^{zd}}{p^{m*}}\right)^{\varrho_z} z^d, \qquad m^x = \left(1-\bar{a}_x\right) \left(\frac{w_t^{zx}}{p^{m*}}\right)^{\varrho_z} z^x.
\end{aligned}$$

Furthermore,

$$\begin{aligned}
\mathsf{S}_{gdp^d}^{m^d} &= \frac{p^{m*}m^d}{y^d - p^{m*}m^d}, \qquad \mathsf{S}_{gdp^x}^{m^x} = \frac{p^{m*}m^x}{\kappa y^d - p^{m*}m^x}, \qquad \mathsf{S}_y^I = \frac{\delta k}{y^d(1+\kappa)}, \\
1 &= \frac{\theta}{\theta-1} mc^d, \qquad 1 = \frac{\theta}{\theta-1} mc^x, \\
x &= p^{m*}m,
\end{aligned}$$

where the last equality is due to the assumption that the steady-state debt of the country is zero.

One can use the above formulas to calculate the required quantities. It is important to note that the homogeneity of production functions imply that at this stage of calculations one does not need the level y^d, hence the assumption of $y^d = 1$ was set.

The calculated steady-state values are $\bar{\alpha}_d = 0.330$, $\bar{\alpha}_x = 0.259$, $\bar{a}_d = 233$, $\bar{a}_x = 146$,$w = 10.808$, $\kappa = 0.923$.

In the next stage $\omega^o = 0.75$, $\omega^{no} = 0.1625$, $\bar{c}^p = c^p/c = 0.248$, $\mathsf{S}_y^g = g/y = 0.142$, $\theta_w = 3$ were taken as given , and the values of y^d, c^o, c^p, $\bar{\omega}^o$, $\bar{\omega}^{no}$ can then be calculated.

In this stage the above steady-sate input demand equations are used. Furthermore the following steady-state labor demand

$$l^d = \bar{a}_d \left(\frac{w^{zd}}{w}\right)^{\varrho_z} z^d, \qquad l^x = \bar{a}_x \left(\frac{w^{zx}}{w}\right)^{\varrho_z} z^x,$$

is derived form formula (122).

Beyond this now we have the following equations.

$$
\begin{aligned}
w &= \frac{\theta_w}{\theta_w - 1}\left[(1-h)c^o\right]^{\sigma}\left(l^d + l^x\right)^{\varphi},\\
y^d &= c + S_y^g y^d(1+\kappa) + \delta\left(k^d + k^x\right),\\
\omega^o &= \frac{\bar{\omega}^o c^o}{c}, \qquad \omega^{no} = \frac{\bar{\omega}^{no} c^{no}}{c},\\
c &= \bar{\omega}^o c^o + \bar{\omega}^{no}\left[w\left(l^d + l^x\right) - \mathsf{S}_y^g y^d(1+\kappa)\right] + \left(1 - \bar{\omega}^o - \bar{\omega}^{no}\right)c^p,\\
\bar{c}^p &= \frac{c^p}{c}.
\end{aligned}
$$

Using the above formulas it is possible to calculate the required steady-state values. If the estimated mode is applied the numerical values are the following: $y^d = 14.616$, $c^o = 10.629$, $c^p = 1.856$, $\bar{\omega}^o = 0.528$, $\bar{\omega}^{no} = 0.119$. Given these values the steady-state values of the rest of variables can be calculated straightforwardly.

B.3 Construction of the Kalman filter

This section describes the construction of the Kalman filter used for evaluating the likelihood function. The rational-expectation solution log-linearized model can be express by the following time-varying-coefficients difference equations

$$\mathcal{X}_t = \mathcal{P}_t \mathcal{X}_{t-1} + \mathcal{Q}_t \mathcal{Z}_t, \qquad z_t = \mathcal{R}_t z_{t-1} + \mathcal{E}_t$$

$\mathcal{X}_t$ is the vector of endogenous variables[47], $\mathcal{Z}_t$ is the vector of exogenous shocks[48] and $\mathcal{E}_t$ is the vector of innovations. In the crawling-peg period $\mathcal{P}_t = \mathcal{P}^{cr}$, $\mathcal{Q}_t = \mathcal{Q}^{cr}$, where matrices $\mathcal{P}^{cr}$ and $\mathcal{Q}^{cr}$ are the solutions of the system of equations (160)–(179), (181) and (183). While in the inflation-targeting period $\mathcal{P}_t = \mathcal{P}^{it}$, $\mathcal{Q}_t = \mathcal{Q}^{it}$, where matrices $\mathcal{P}^{it}$ and $\mathcal{Q}^{it}$ are the solutions of the system of equations (160)–(178) and (180)–(183).

The state-space form of the above difference equations is

$$\mathcal{V}_t = T_t \mathcal{V}_{t-1} + G_t \mathcal{E}_t,$$

where $\mathcal{V}_t' = [\mathcal{X}_t', \mathcal{Z}_t']$ and

$$T_t = \begin{bmatrix} \mathcal{P}_t & \mathcal{Q}_t\mathcal{P}_t \\ 0 & \mathcal{R} \end{bmatrix}, \qquad \text{and} \qquad G_t = \begin{bmatrix} \mathcal{Q}_t \\ 0 \end{bmatrix}.$$

The observation equation is given by

$$\mathcal{S}_t = H\mathcal{V}_t,$$

[47] Namely, $\hat{\pi}_t$, $\hat{\pi}_t^w$, $\tilde{c}_t$, $\tilde{c}_t^o$, $\tilde{c}_t^{no}$, $\widetilde{w}_t$, $\tilde{x}_t$, $\widetilde{m}_t$, $\tilde{l}_t$, $\tilde{n}_t$, $\tilde{k}_t$, $\tilde{I}_t$, $\tilde{q}_t$, $\tilde{e}_t$, $\hat{\imath}_t$, $\tilde{b}_t$, $\widetilde{Q}_t$ and $\tilde{r}_t^k$.

[48] That is, $\tilde{g}_t$, $\widetilde{P}_t^{m*}$, $d\bar{q}_t$, $\tilde{x}_t^*$, $\widetilde{A}_t$, $\tilde{\upsilon}_t$, $\tilde{\upsilon}_t^w$, $\tilde{\varepsilon}_t^c$, $\tilde{\varepsilon}_t^{de}$, $\tilde{\varepsilon}_t^{pr}$, $\tilde{\varepsilon}_t^n$, $\tilde{\varepsilon}_t^I$ and $\tilde{\varepsilon}_t^Q$ in the crawling peg period, and $\tilde{\varepsilon}_t^{de}$ is replaced by $\tilde{\varepsilon}_t^r$ in the inflation-targeting period.

where $\mathcal{S}_t$ is the column vector of observed variables and H is a selection matrix. As Hamilton (1994, chapter 13) shows, it is possible to use a Kalman filter derived from a time-varying model for likelihood evaluation, only if the time-varying parameters are functions of exogenous and predetermined variables. The estimated AL versions fulfil this condition.

Following Koopman and Durbin (2003), the Kalman filter is generated by the following recursive formulas.

$$\begin{aligned}
\mathcal{U}_t &= \mathcal{S}_t - H\xi_t, \\
F_t &= H\mathsf{P}_t H', \\
\bar{\xi}_t &= \xi_t + \mathsf{P}_t H_t'^{-1}\mathcal{U}_t, \\
\xi_{t+1} &= T_t\bar{\xi}_t, \\
K_t &= T\mathsf{P}_t H_t'^{-1} \\
\mathsf{P}_{t+1} &= T_t\mathsf{P}_t(T_t - K_t H)' + T_t\mathsf{V}T_t',
\end{aligned}$$

P_0 and ξ_0 are given. The matrix V is the variance-covariance matrix of $\mathcal{E}_t$. Series of the forecast error $\mathcal{U}_t$ and the matrix F_t are used to construct the logarithm of the likelihood function. This is given by

$$\mathcal{L}(\cdot) = -\frac{TN}{2}\ln(2\pi) - \frac{1}{2}\sum_{t=1}^{T}\det(F_t) - \frac{1}{2}\sum_{t=1}^{T}\mathcal{U}_t' F_t^{-1}\mathcal{U}_t,$$

where N is the number of observed variables, and T is the number of time periods used for estimation.

To initialize the above algorithm $\xi_0 = 0$ is set, and P_0 is the unconditional variance-covariance matrix of the constant-coefficient process,

$$\mathcal{V}_t = T_0 V_{t-1} + G_0\mathcal{E}_t,$$

that is, using formulas (10.2.17) and (10.2.18) of Hamilton (1994), it can be expressed as

$$\mathrm{vec}(\mathsf{P}_0) = (I - T_0 \otimes T_0)^{-1}\,\mathrm{vec}(G_0\mathsf{V}G_0')$$

where symbol $\otimes$ represents the *Kronecker product*, and operator *vec* transforms a quadratic matrix into a column vector by stacking the columns of the matrix one below the other, with the columns ordered from left to right.

B.4 Data set

The log-linearized model is estimated on the sample between 1995Q2 and 2007Q2. Twelve data series were used as observed variables. All data are quarterly, seasonally adjusted and imported from the database of the November, 2007 version of the Quarterly Projection Model (NEM) of the Magyar Nemzeti Bank (see Benk et al. (2006)).

HP-filtered data were used in the case of GDP, capital stock, employment, consumption, investments, export, imports and real wages (private wages deflated by CPI inflation, WP/CPI in NEM) ($\lambda = 1600$). Consumption is defined as private 'consumption expenditures' (CE in the NEM). Investments contain all private investments (household and corporate investments - HI+CI in NEM). Government consumption equals to the sum of public investments, government purchases of goods and services and transfers in kind (GC+GI+TRAN in NEM). Employment is constructed as total (private plus public) employment. Capital stock is defined as private capital stock, excluded housing (KP in NEM).

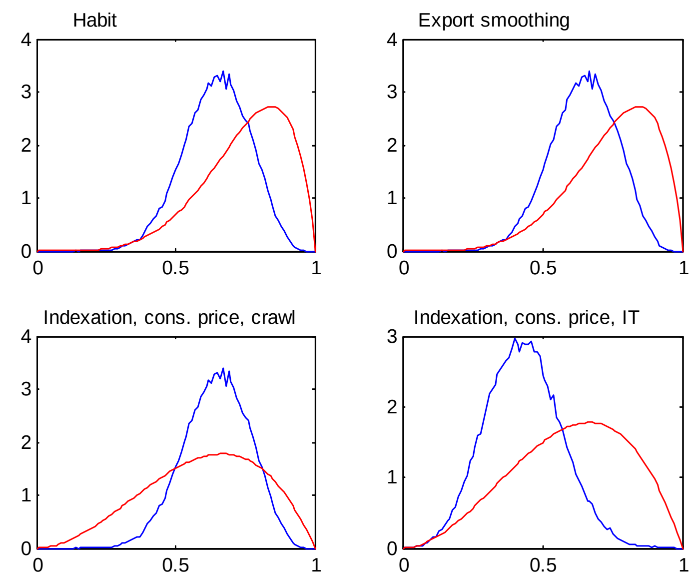
Price inflation data were calculated by a two step method. In Hungary there is a trend difference between non-traded and traded inflation caused by systematic productivity differential (Balassa-Samuelson effect) the real exchange rate has an appreciating trend (see Kovács (2002)). The model, however, does not have two-sectors and thus unable to account for this, first a trend (around 1.6 percent annually) was filtered out from inflation data (quarterly non-traded inflation was reduced by 1 per cent), and then a 'Balassa-Samuelson' filtered inflation series was calculated. As a second step the average nominal exchange rate change was deduced and then it was demeaned. By this transformation foreign inflation and the remaining trend in real exchange rate was filtered out. Nominal wage inflation is then real wages plus this type of transformed consumer price inflation.

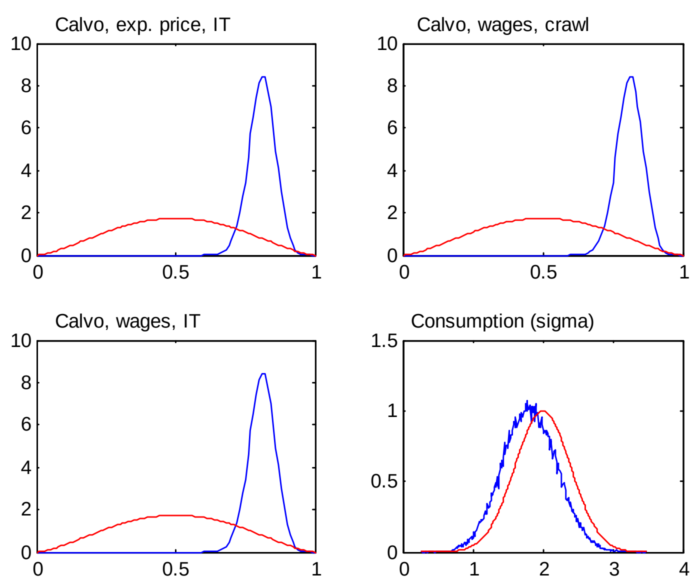
Export and import prices are defined in foreign currency units, that is export and import deflators divided by the nominal effective exchange rate of the Forint (PX/EFEX and PM/EFEX in NEM).

B.5 Metropolis-Hastings Monte Carlo density graphs of the Baseline Model

Structural parameters

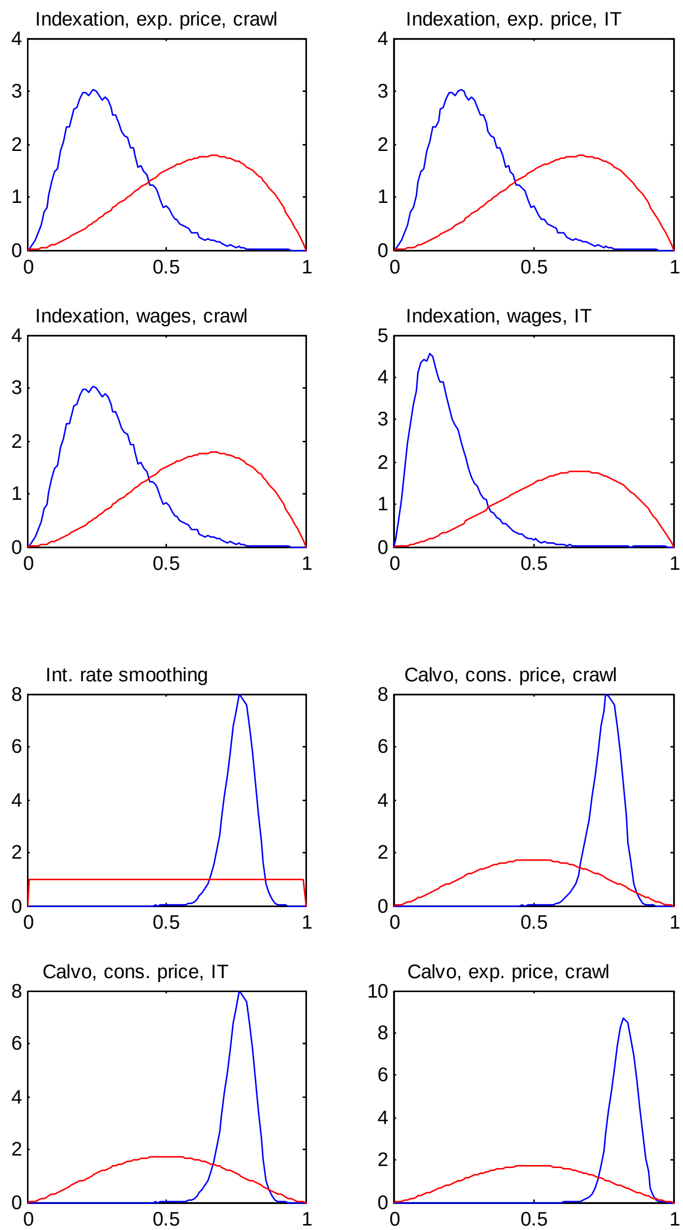
red line: prior density, blue line: posterior density





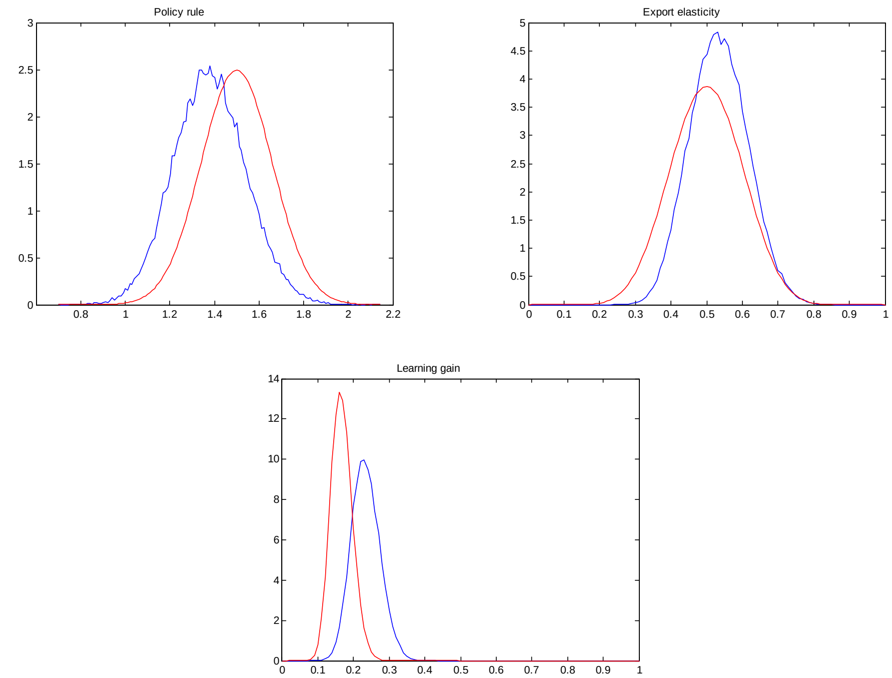
Structural parameters (cont'd)

red line: prior density, blue line: posterior density

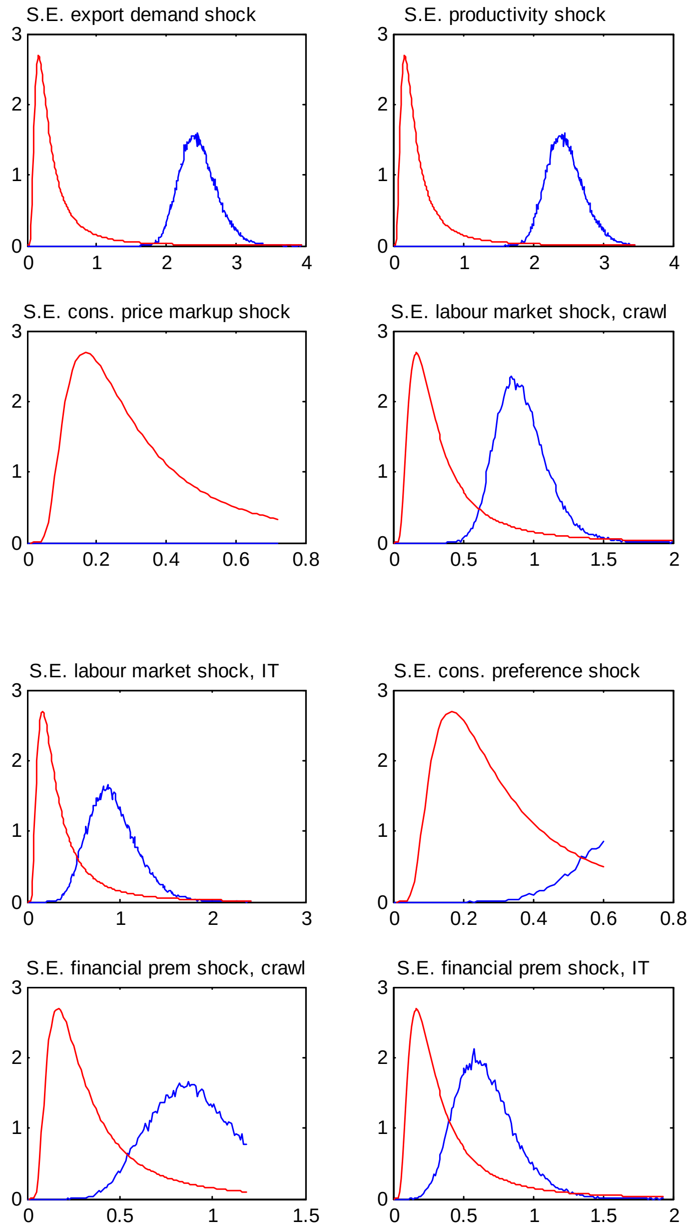


Structural parameters (cont'd)

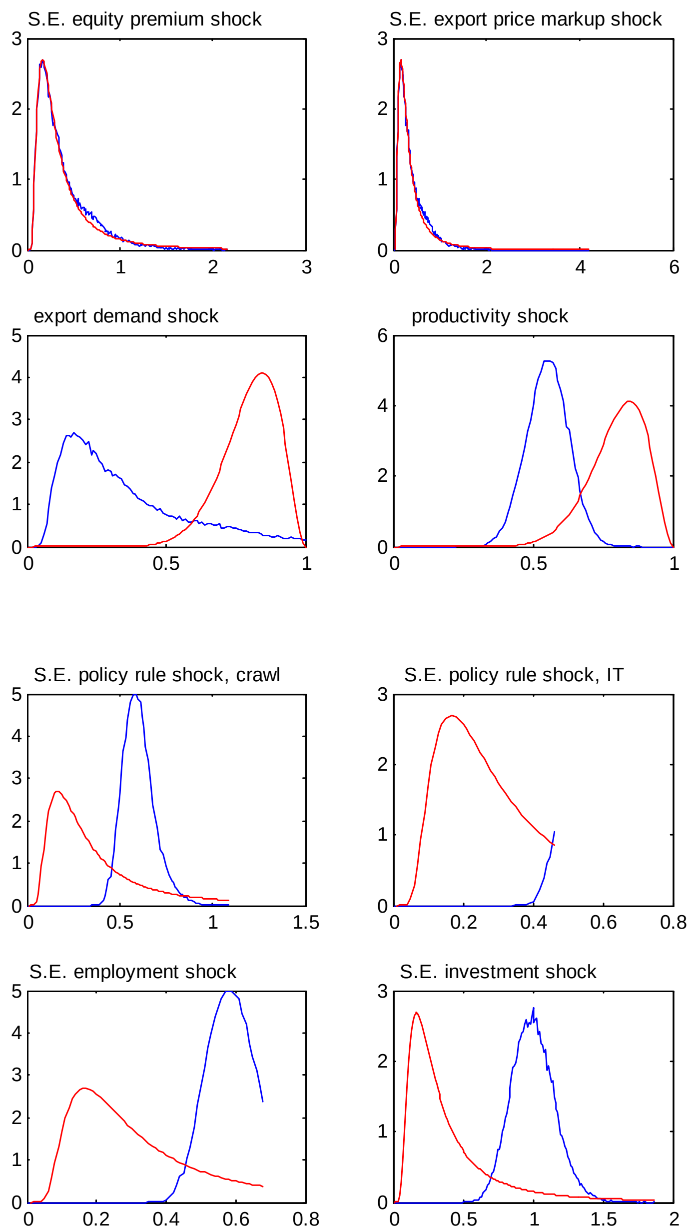
red line: prior density, blue line: posterior density



Standard errors of shocks
red line: prior density, blue line: posterior density



Standard errors of shocks (cont'd)
red line: prior density, blue line: posterior density



Autoregressive coefficients of shocks

red line: prior density, blue line: posterior density