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Impacts of the Great Recession on the structure and behaviour of the Visegrád group economies

PhD thesis

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πάντα χωρεῖ καὶ οὐδὲν μένει.
Ηράκλειτος

Everything changes and nothing stands still.
Heraclitus

Abstract

In the thesis, I deal with identification and comparison of the underlying structure of the Visegrád group economies, including possible structural changes during the Great Recession. It is a goal of the thesis to explain largely dissimilar impact of the Great Recession in the examined economies based on the ascertained structural differences and the differences in composition of exogenous shocks that these economies faced in this period. Structure of individual economies was identified using a small open economy DSGE model with financial frictions. Apart from the models with time-invariant structure, I estimated also nonlinear models with time-varying structural parameters with use of nonlinear particle filter. In case of the Slovak economy, that became a member of the euro area during examined period, a monetary policy regime switch is implemented in the model structure. Results of the estimation suggest, that the different repercussions of the Great Recession in the Visegrád economies can be related to the different openness to the international trade, differences in the sensitivity of the real exchange rate to the balance of trade and different preferences and possibilities of the central banks to deliver easing of monetary policy. Moreover, the reaction of the real economy to the lowering of policy interest rates during the crisis was dampened by growing spreads due to increasing risk premium of commercial banks. The time-varying estimates showed significant changes in the pricing behaviour and indebtedness of the firms in the examined period. Based on the sensitivity analysis, the nonlinear particle filter proved to be relatively robust tool, suitable for identification of structural changes.

Keywords

DSGE models, particle filter, Great Recession, Visegrád group, structural changes

Abstrakt

V práci se zabývám identifikací a srovnáním struktury ekonomik Visegrádské skupiny včetně možných strukturálních změn v období Velké recese. Cílem práce je na základě zjištěných rozdílů ve struktuře daných ekonomik a ve skladbě exogenních šoků, kterým tyto ekonomiky v daném období čelily, vysvětlit do značné míry rozdílný průběh Velké recese v těchto zemích. Struktura jednotlivých ekonomik byla identifikována s využitím DSGE modelu malé otevřené ekonomiky s finančními frikcemi. Kromě modelů s pevnými parametry byly odhadnuty i nelineární modely se v čase proměnnými strukturními parametry, a to s pomocí nelineárního particle filtru. V případě slovenské ekonomiky, která se ve sledovaném období stala členem eurozóny, je v modelu implementována změna režimu měnové politiky. Výsledky odhadů ukazují, že rozdílné dopady Velké recese v zemích Visegrádské skupiny mohou být dány do souvislosti zejména s různou mírou otevřenosti jednotlivých ekonomik, lišící se citlivostí reálného směnného kurzu na vývoj obchodní bilance a rozdílnými preferencemi a možnostmi centrálních bank k uvolnění měnové politiky. Reakce reálné ekonomiky na snižování měnověpolitických úrokových sazeb byla navíc během krize tlumena nárůstem úrokového rozpětí v důsledku nárůstu rizikové prémie komerčních bank. V čase proměnné odhady dále ve sledovaném období ukázaly hlavně na změny v chování firem v oblasti přeceňování a zadlužení. Na základě provedené analýzy citlivosti se nelineární particle filter prokázal jako poměrně robustní nástroj, vhodný pro identifikaci strukturních změn.

Klíčová slova

DSGE modely, particle filter, Velká recese, Visegrádská skupina, strukturální změny

I hereby declare that this dissertation is my original authorial work, which I have worked out by my own under supervision of professor Osvald Vašíček. All sources, references and literature used during elaboration of this work are properly cited and listed in complete reference to the due source in accordance with legal regulations, Masaryk University internal regulations and Masaryk University and Faculty of Economics and Administration internal directives.

Bratislava, September 28, 2015 Stanislav Tvrz

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Stanislav Tvrz

Contents

Introduction

The turbulent period of the Great Recession brought about distinct changes in the performance and behaviour of the Visegrád economies and highlighted their mutual differences. It is the goal of the thesis to identify the main factors that can explain the differences in the macroeconomic development of the Visegrád economies during the Great Recession and subsequent recovery and to formulate recommendations for the monetary policy based on the obtained results.

The different development of the individual Visegrád economies can be explained by different set of exogenous shocks that these economies faced during the crisis and also by the differences in the underlying structure of these economies. One of the Visegrád economies, the Slovak economy, joined the euro area in January 2009, that is just when the Central European region was hit by the global crisis the hardest. Thus, its structure apparently changed because of the change in the exchange-rate regime and because the authority over monetary policy decision-making was transferred to the European Central Bank, the central bank of the monetary union as a whole. Apart from obvious and observable structural changes, such as the Slovak adoption of the common European currency, there could have been other structural changes that are generally much harder to ascertain. Conceivably, the characteristics of the behaviour of households, firms, banks and/or monetary authority might have temporarily or permanently changed during this period due to the extraordinary events experienced.

In order to find answers for the research questions posed in this thesis, a model approach is used. The empirical results that are presented in the thesis are obtained with the use of a set of estimated dynamic stochastic models of a general equilibrium (DSGE). Since the DSGE models have become increasingly popular among the central bankers in recent past, the results of the presented research can be of interest not only for the academia but also for the central banks. In particular, the estimation of structural changes is not standard in the policy DSGE models used at the central banks. Therefore, the implications of obtained results for the monetary policy will be considered in the thesis as well.

The structure of the thesis is as follows: Chapter 1 gives the motivation of the research and formulates the objectives of the thesis; Chapter 2 describes current state of the art as captured by the literature; Chapter 3 describes the main features of the small open economy DSGE model that is used for the analysis; Chapter 4 explains the basic principles of the estimation techniques that are employed in the thesis; Chapter 5 presents and discusses the empirical results; Chapter 6 deals with the sensitivity analysis of obtained results; and the final section summarizes the conclusions of the thesis. Appendices of the thesis contain explanation of the mathematical notation, extensive derivations of some model relations, and supplementary graphs and tables.

Chapter 1

Motivation and objectives of the thesis

The investigation of possible structural changes in the Visegrád economies was mainly motivated by the turbulent economic developments in these countries during the Great Recession. The Visegrád economies experienced an unprecedented shock that, apart from endogenous adjustments, may have caused even structural changes. Since the Great Recession had its roots in the U.S. subprime mortgage crisis and subsequent turmoil in the financial sector, the causes of the economic crisis in Europe were mostly exogenous. Therefore, the Visegrád economies were subject to a similar set of exogenous shocks at the same time. However, the economic development during the crisis was to a large extent dissimilar. This could mean that the economies experienced different internal shocks during the crisis, their structure was dissimilar even before the crisis or the structural changes induced by the global economic crisis were largely diverse.

1.1 Origins of the Great Recession

The term *Great Recession* has become a convenient label for the period of global financial and economic crisis of the early 21st century. It usually covers the interval between 2007 and 2009, when the U.S. subprime mortgage crisis took place, but it is commonly used in the context of other economies as well. In such a case, the exact definition varies and may depend on the course of the crisis in that particular economy. In this thesis the term *Great Recession* is used in the first sense to denote the period of global economic troubles of 2007-2009.

The Great Recession began in 2007 in the U.S. as a subprime mortgage crisis (see Eichengreen et al. (2012)). Loose monetary policy and promotion of lending for housing purposes by the government together with weak regulation of the financial market lead to a creation of the mortgage-backed securities.[1] These derivatives were constructed by bundling together of a large number of (subprime) mortgage contracts in an attempt to decrease the inherent default risk by diversification. The risk of such derivatives were hard to realistically assess, and as it turned out, it was in fact underestimated. The attempted diversification failed, because the mortgage-backed securities were still vulnerable to systemic shocks that affect the whole area (economy) and were only able to cope with independent idiosyncratic shocks.

After the burst of the housing bubble during 2006, the homeowners began to default with increasing frequency and the value of mortgage-backed securities began to col-

[1] Norberg (2012) suggests that it was the too relaxed monetary policy of the U.S. Federal Reserve System since the second half of 2007, that flooded the U.S. economy with easy money and facilitated the housing boom in the U.S., that was the root cause of subsequent financial and economic crisis.

lapse. During 2007, the credit conditions tightened and economic activity slowed down. The build-up of risky loan losses accelerated and the value of mortgage-backed securities quickly deteriorated. The situation further worsened in September 2008 after the default of Lehman Brothers, a large U.S. investment bank, and after the rescue of the American International Group (AIG), the biggest U.S. insurance company. According to the International Monetary Fund (2009), these events induced a substantial increase in perceived risk and the solvency of many established financial intermediaries came into question. The demand for liquidity soared together with the interest rate spreads. The financial flows were heavily disrupted. The banks tightened their lending conditions and equity prices fell sharply.

According to the International Monetary Fund (2009), thanks to a limited exposure to the U.S. subprime market, the subprime crisis in 2007 had relatively mild impact on the emerging markets in the Eastern Europe, Asia and Latin America. However, the events of 2008 had global consequences and the emerging markets were hit hard as well as the advanced economies by the panic on the interbank lending market. The impaired functioning of the interbank lending market translated into severely limited lending to the real economy and the financial crisis turned into the economic crisis. Consequently, the aggregate demand slumped, international trade declined and unemployment climbed up significantly.[2]

A number of major banks in the United States and Europe were provided with public support in the form of new capital and guarantees against losses from holdings of toxic assets. Since the inflation pressures were low, policy rates were cut sharply, bringing them often to unprecedented values. However, the impact of interest rate cuts was limited by credit market disruptions, high interest rate spreads and also by the zero lower bound. As the monetary policy reached its limits, fiscal policy stimuli were applied in many economies. By 2010, the banking crisis was overcome in most countries.

1.2 Developments in the Visegrád economies since the Great Recession

The banking sector of the Visegrád countries coped with the financial crisis of 2007-2008 fairly well, mainly thanks to the fact that their domestic banks were not trading with complex structured financial instruments in significant volume and their exposure to the U.S. subprime mortgage crisis was, therefore, limited. High capitalization, liquidity and rentability of the banking system helped it to weather the financial crisis without much support from the government. Hungary was an exception because a high share of foreign currency denominated debt together with sharp depreciation of forint necessitated a rescue program. Nevertheless, the Visegrád economies were affected by the increase of systemic risk and uncertainty during the second half of 2008 which led to a downturn in world aggregate demand and international trade. Even though the Visegrád economies were relatively sheltered from the first-hand effects of the global financial crisis, they were hit by the subsequent global economic crisis like the rest of the globalized world economy.

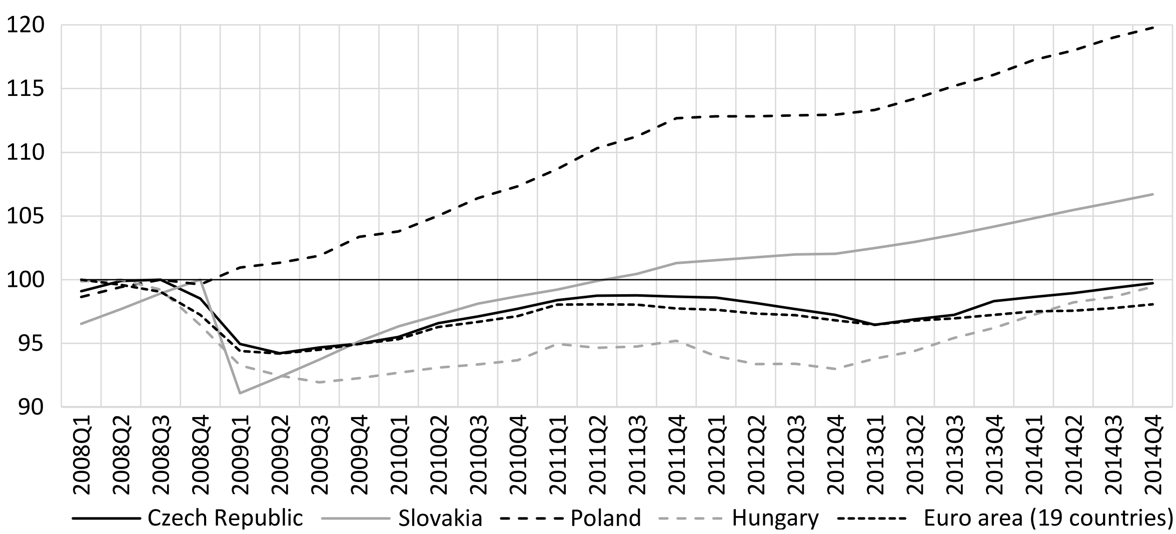
[2]Eaton et al. (2009) used multi-country general equilibrium model to investigate forces acting on the global economy during the Great Recession and found a that the collapse of international trade was largely caused by a decline of investment efficiency in durable manufacturing capital stock that caused further reduction of spending in the tradable sector. Bems et al. (2010) used a global input-output framework to quantify U.S. and European Union demand spillovers during the Great Recession and found that demand forces alone can account for roughly 70 per cent of the world trade collapse.

What is particularly interesting is the differing effects of the Great Recession on the real economic output of the Visegrád economies. The Czech economy suffered a double-dip recession with a relatively deep economic downturn between 2008Q4 and 2009Q2, and a protracted shallow recession between 2011Q4 and 2013Q1. Developments in the Hungarian economy were similar. A deep recession between 2008Q3 and 2009Q3 was followed by a less severe recession in 2012. In Slovakia, a textbook recession was avoided, since a sharp decline of real GDP in 2009Q1 was immediately followed by a swift recovery. But it was the Polish economy that became a model of successful coping with the global crisis. Not only did the Polish economy avoid a recession, it avoided the downturn in real economic activity in 2009Q1 as well.

Between the accession to the European Union in 2004 and the pre-crisis peak, the Polish economy grew by an average quarterly rate of 1.27 percent, the Czech economy grew by a similar quarterly average rate of 1.32 percent, the Slovak economy grew by an average quarterly rate of 1.75 percent, and the Hungarian economy grew on average by 0.75 percent a quarter. Since 2010, the Polish and Slovak economies have been growing by an average quarterly rate of approximately 0.75 and 0.6 percent respectively. In the same period, the Czech economy has achieved an average quarterly rate of real GDP growth of only 0.25 percent, while the Hungarian economy has grown by an average rate of 0.33 percent. As can be seen in Figure 1.1, the Polish economy was approaching 120 percent of its pre-crisis peak in 2014Q4 while the Czech and Hungarian real output was finally returning to its maximum of six years before. The Slovak economy recovered from the crisis in 2011Q3 and in 2014Q4 it was at almost 107 percent of its pre-crisis peak.

Overall, we can say that the the Polish economy survived the Great Recession nearly unscathed. The Slovak economy experienced the largest downturn in real GDP in 2009Q1 but recovered quickly. The aftermath of the Great Recession in the Czech economy was comparable to the development in the euro area that also experienced a double-dip recession with a shallow and lengthy second phase. The impact of the Great Recession was the most severe in the Hungarian economy but the situation seems to be improving quickly since 2013.

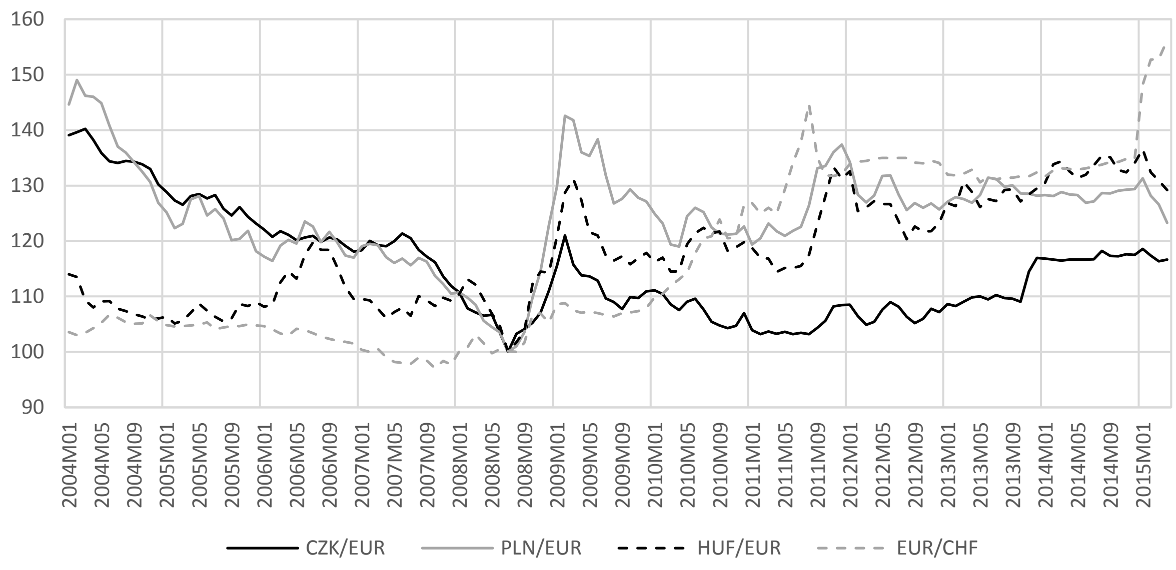
Figure 1.1: Real GDP during the Great Recession (index, pre-crisis maximum = 100)



Source: Author, Data: Eurostat.

While Slovakia entered the exchange rate mechanism ERM II shortly after becoming a member of the European Union, and adopted the euro currency in January 2009, the remaining Visegrád countries do not plan to join the monetary union anytime soon. In the Czech and Polish economies, the currency depreciation (depicted in Figure 1.2) helped exporters to maintain their competitiveness during the crisis. The adoption of the euro currency prevented the currency depreciation in the Slovak economy and can partially explain the deep impact of the crisis in 2009Q1. The situation in Hungary and to a certain extent Poland was, however, complicated by the large share of debt denominated in foreign currency (especially Swiss francs), which had been accumulated in the favourable period when the domestic currency was strong and low foreign interest rates seemed appealing. In July 2008, the share of household debt denominated in foreign currency was almost 60 percent in Hungary, while in Poland it was less than 30 percent and in the Czech Republic the share was negligible. The rapid currency depreciation in 2008Q4 (see Figure 1.2) amplified the burden of foreign currency denominated debt and led to a currency crisis, which exacerbated the impact of the Great Recession. Between July 2008 and January 2009, the share of loans to households denominated in foreign currency increased to almost 70 percent in Hungary, while in Poland it reached approximately 40 percent. The appreciation of the Swiss franc in 2011 further complicated the situation and eventually resulted in a government led initiative to convert foreign currency denominated mortgages into domestic currency ones. Even though the program is not yet completed, it has already shielded Hungarian households from the negative effects of the Swiss franc appreciation after the peg to the euro was removed in January 2015. The share of foreign currency denominated household debt in Poland fell back under 30 percent during 2014; nevertheless, Swiss franc appreciation had a relatively serious impact and provoked a discussion about ways of sharing the incurred losses between debtors and banks.

Figure 1.2: Nominal exchange rates (index, 2008M07 = 100)

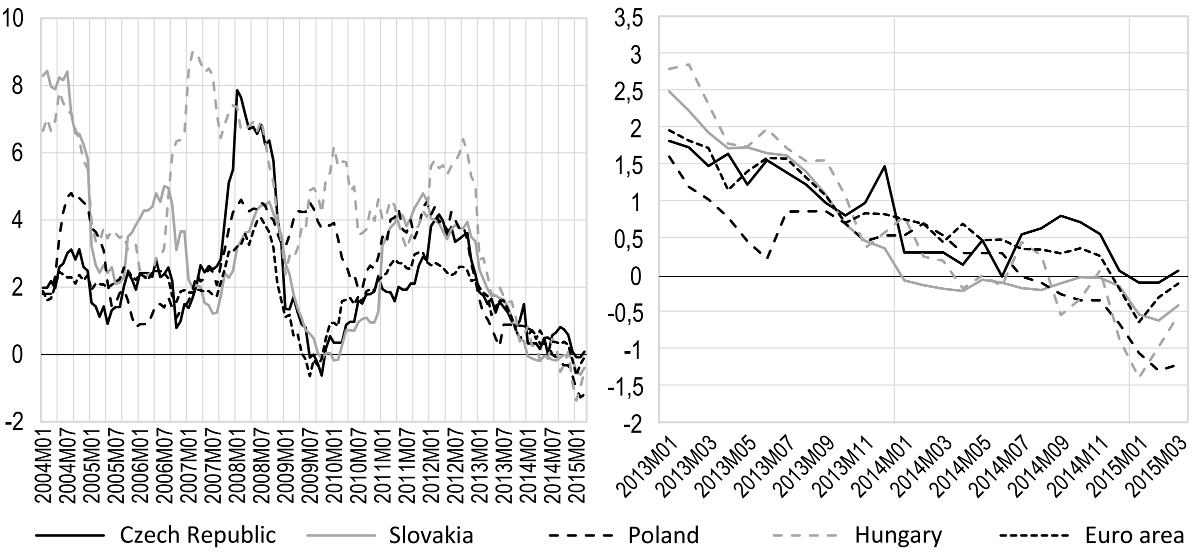


Source: Author, Data: ECB.

During the Great Recession, the HCPI inflation (depicted in Figure 1.3) declined together with the domestic and foreign demand in the Czech and Slovak economies as well as in the euro area. In Poland, the level of aggregate demand stayed high and so did the inflation. The inflation in Hungary remained high during the Great Recession as well, fluctuating around 4 percent p.a. The Czech National Bank (CNB) as well as the ECB started the lowering of the policy interest rate in this period in order to steer the inflation towards the respective inflation targets.

Since 2013, the Visegrád economies have faced strong disinflationary pressures. While in Poland and Hungary the policy interest rates are still relatively far above zero and the central banks can maintain accommodative monetary policy with the use of standard tools, in the Czech Republic the interest rates reached the so called technical zero (0.05 percent) in November 2012. In November 2013, the exchange rate intervention of the Czech National Bank (CNB) lead to a depreciation of the Czech koruna and to introduction of a currency floor of 27 CZK/EUR. The intervention showed that the monetary policy of the CNB is not restricted to the setting of policy rates (especially in the environment of near-zero interest rates). The Czech central bank seems to be ready to use all available instruments to deliver further monetary easing consistent with its inflation target. More than a year after the CNB intervention, inflation in the Czech economy remains far below the target, mainly because of the much lower inflation than previously expected imported from the euro area and the fall in the price of oil in the second half of 2014. Nevertheless, the main goal of avoiding deflation was indeed achieved.

Figure 1.3: HCPI inflation



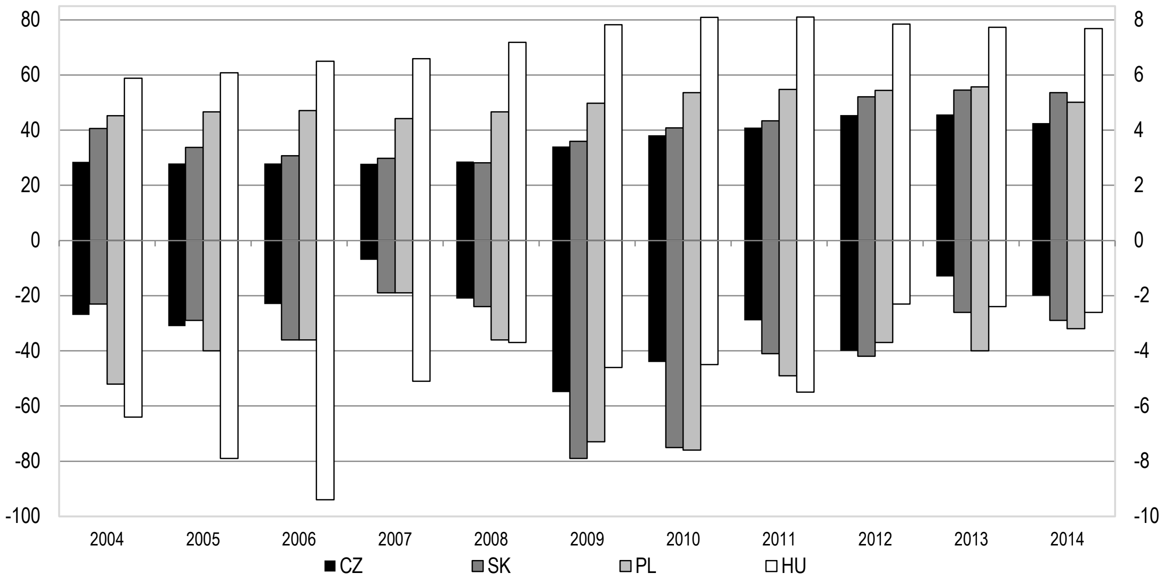
Source: Author, Data: Eurostat.

As a member of the Eurosystem, the National Bank of Slovakia alone cannot make such an intervention; on the other hand, it participates in the setting of monetary policy for the whole euro area. The situation in the Eurozone is similar to that in the Czech Republic - the policy interest rate is at the technical zero (-0.2 percent) and the inflation is far below the target. The ECB declared its commitment to preventing deflation in the euro area using any means necessary. But due to the different position of the euro currency in the world economy a CNB-style exchange rate intervention is not easily imaginable. In an environment of near-zero interest rates the ECB launched another round of quantitative easing (QE). From March 2015, the ECB pledged to buy 60 billion EUR worth of government bonds. Total expected volume of the QE programme is 1.1 trillion EUR.

Among other factors, the divergent development of the Visegrád economies since the Great Recession was reinforced by differences in fiscal policy. As can be discerned in Figure 1.4, the Polish and Slovak economic growth was reignited by increased government spending after the impact of the crisis. The deficits of the crisis years 2009 and 2010 reached values near to 7.5 percent. However, since comparatively high economic growth was restored in Poland, the debt to GDP ratio increased between 2007 and 2013 by only

11.5 pp. In Slovak economy, the growth was rather modest and the debt to GDP ratio increased by 25 percent. In Hungary, the currency crisis and subsequent IMF intervention resulted in relatively restrained fiscal policy during the crisis, with deficits around 5 percent. The debt to GDP ratio increased by only 11.4 pp between 2007 and 2013 thanks to high inflation (see Figure 5). In the Czech economy, tight fiscal policy was maintained during the crisis. With deficits similar to those in Hungary, the debt to GDP ratio increased by nearly 18 pp between 2007 and 2013 due to a lack of economic growth and low inflation.

Figure 1.4: General government deficit and debt (in per cent of GDP)

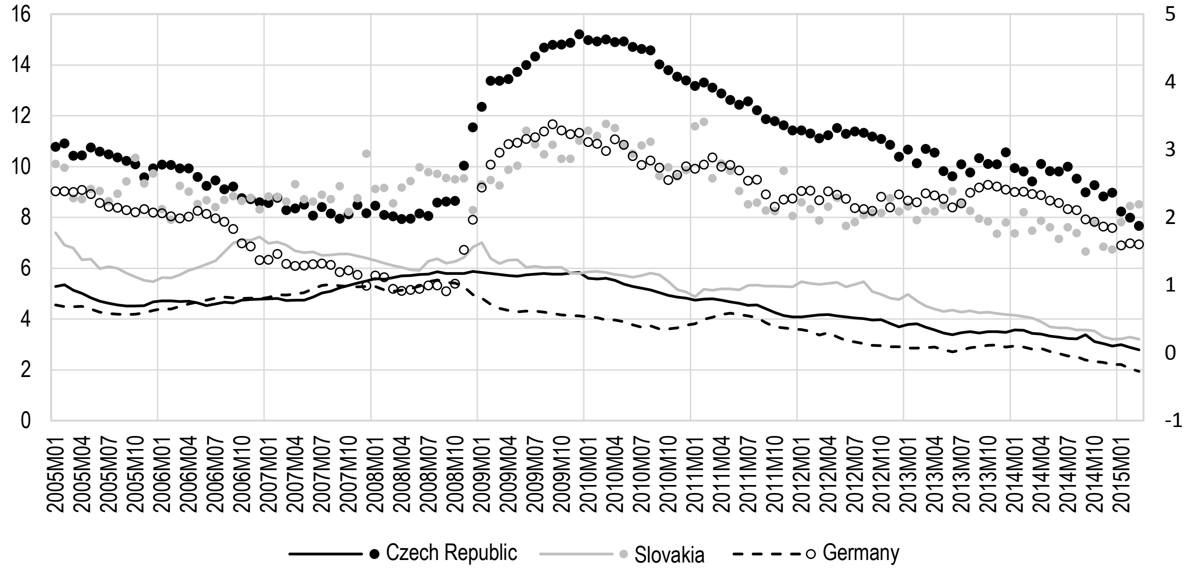


Source: Author, Data: Eurostat.
Note: Government deficit - right axis, negative values, government debt - left axis, positive values.

Figures 1.5 and 1.6 depict the lending rates and margins[3] of loans for house purchases and loans to non-financial corporations respectively in the Czech, Slovak and German (as a principal member of the euro area) economies.

[3] According to the European Central Bank (2000), the lending margin is defined as *the difference between banks' average contractual rates on new loans (flows) and a reference rate. The reference rate is the market interest rate of a corresponding average maturity representing the financial opportunity cost for banks. It is not intended to represent the (marginal) cost of funds for the bank.*

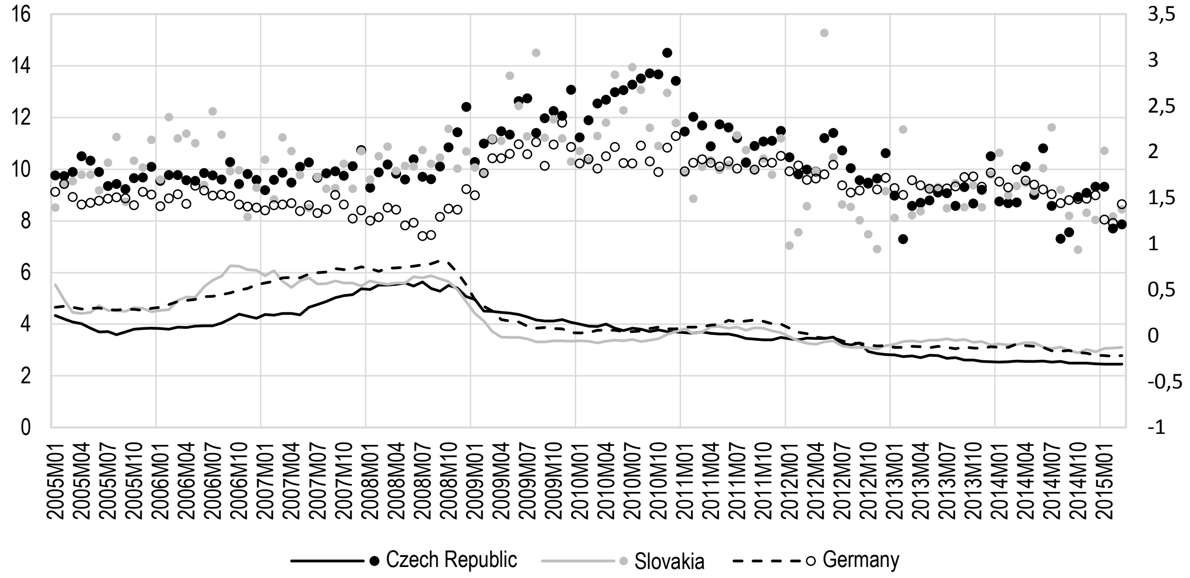
Figure 1.5: Lending rates and margins, loans for house purchase (CZ, SK, DE)



Source: Author, Data: ECB.
Note: Lending rates - left axis, lines, lending margins - right axis, points.

We can distinguish a steep rise in the spread between the interest rate of loans for house purchase and the reference long term interest rate at the turn of 2008 and 2009. The spread between the interest rate of the loans to non-financial corporations gradually increased between 2008 and 2010 in the Czech and Slovak economies, while in Germany the spread increased sharply during the crisis and began to level off in 2010.

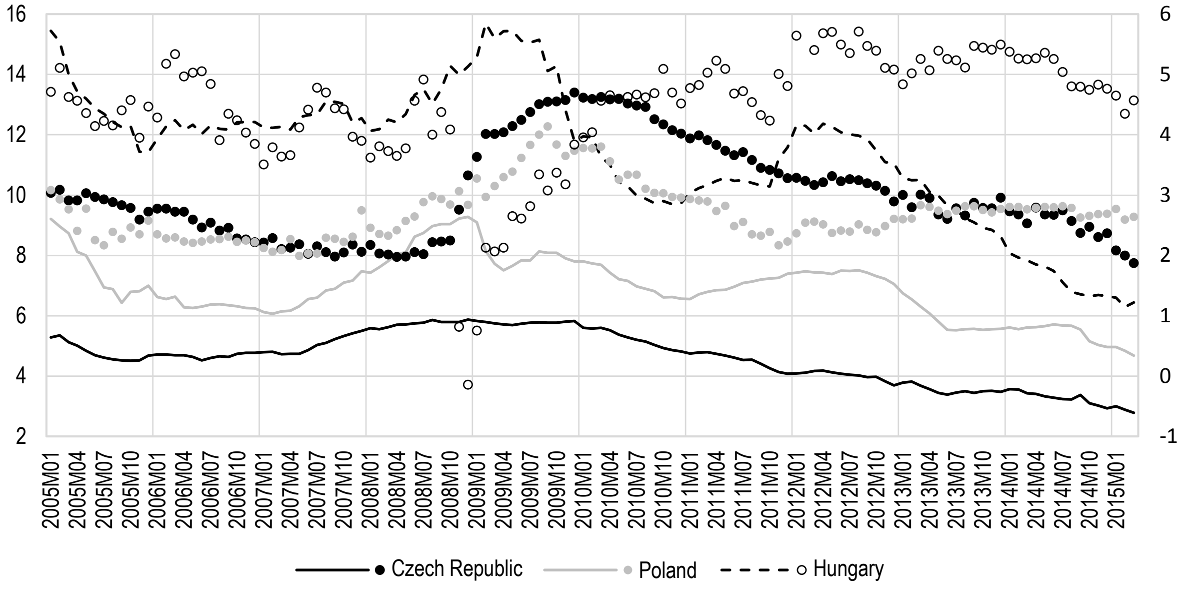
Figure 1.6: Lending rates and margins, loans to NFC (CZ, SK, DE)



Source: Author, Data: ECB.
Note: Lending rates - left axis, lines, lending margins - right axis, points.

Figures 1.7 and 1.8 show lending rates and margins of loans for house purchases and loans to non-financial corporations respectively in the Czech, Polish and Hungarian economies.

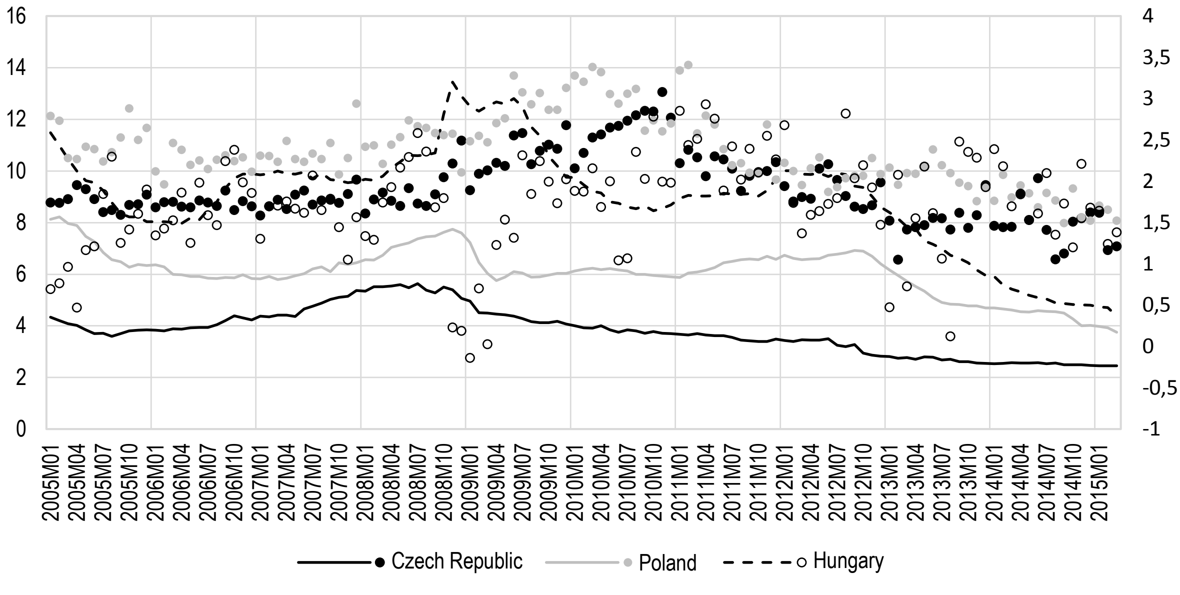
Figure 1.7: Lending rates and margins, loans for house purchase (CZ, PL, HU)



Source: Author, Data: ECB.
Note: Lending rates - left axis, lines, lending margins - right axis, points.

An increase in interest rates in 2007-2008 can be distinguished in all three economies. Since the lending margins in the Czech economy stayed unchanged, this development reflects the tightening of monetary policy in that period. Through 2009, mortgage interest rates were kept unchanged in the Czech economy, while the policy interest rate and the opportunity cost of the commercial banks declined. Similar development can be observed in the Polish economy. However, the lending margins in Poland began to increase during 2008, which suggests that the Polish commercial banks perceived the increased riskiness on the mortgage market earlier than those in the Czech Republic.

Figure 1.8: Lending rates and margins, loans to NFC (CZ, PL, HU)



Source: Author, Data: ECB.
Note: Lending rates - left axis, lines, lending margins - right axis, points.

The situation in Hungary is very specific. While mortgage interest rates increased by 3.5 pp between January 2008 and February 2009, the lending margins declined from around 4 percent below zero in 2008Q4. This extraordinary development was mainly caused by the fact that the Hungarian central bank increased its policy rate in October 2008, from 8.5 percent to 11.5 percent, in order to defend the forint and mitigate depreciation pressures during the crisis. As the policy interest rate did not return below the 8.5 percent before August 2009, the opportunity costs of Hungarian banks actually increased in the crisis, and as a result, their lending margins plunged. While in the Czech and Polish economies, the effects of financial frictions during the Great Recession can be distinguished quite clearly, the situation in Hungary is blurred by the currency crisis.

Overall, interest rate spreads increased significantly during the eruption of the Great Recession. Banks perceived increased uncertainty and systemic risk in the economy and raised their required risk premium. As the central banks reacted to the prospect of a recession and the expected drop in inflation, the opportunity costs of commercial banks declined. However, this was not immediately reflected in the client interest rates, and lending margins swelled. Despite the fact that the impacts of the crisis on the domestic financial sector in the Visegrád economies were relatively mild, the interest rate spreads increased substantially. Apparently, there can be times when the development of the policy interest rate differ significantly from the development of commercial interest rates that the households and firms in the economy actually face. The observed behaviour of the commercial banks constitutes a financial friction because it led to a decoupling of the client and policy interest rates and disrupted the link between policy rates and the real economy. The increased delay in the transmission of monetary policy during the Great Recession is one of the main reasons why the zero lower bound was hit, which led to the necessity for alternative ways to deliver a further easing of monetary conditions.

1.3 Objectives of the thesis

In general, it is the goal of the thesis to identify the main factors that explain the differences in the macroeconomic development of the Visegrád economies during the Great Recession and subsequent recovery.

More specifically the intermediate goals of the thesis can be formulated as follows:

1. To identify long-run differences in the structure and behaviour of the Visegrád economies.

2. To estimate short-run changes in the structure and behaviour of the Visegrád economies.

3. To compare the incidence and impacts of exogenous shocks in the Visegrád economies.

4. To formulate recommendations for the monetary policy based on previous results.

A model approach was selected in order to be able to meet the goals of the thesis. An appropriately complex DSGE model of a small open economy will be constructed and estimated for the individual Visegrád economies. Due to a volatile developments in the financial markets during the crisis, the model should be able to capture the salient features of the financial sector. Therefore, it should be a model with financial frictions.

Long-run structural differences of Visegrád economies will be identified by the use of Bayesian estimation of the structural parameters of the DSGE models with an assumption of constant parameter values on the whole horizon. Short-run structural changes will be identified using a nonlinear specification of the DSGE models with time-varying parameters. Behaviour of the modelled economies shall be compared based on the estimated impulse response functions. Occurrence of the exogenous shocks will be estimated by the means of filtration of the nonlinear DSGE model. The effects of identified exogenous shocks will be calculated using a shock decomposition of main macroeconomic variables. Implications of obtained results relevant to the monetary transmission will be emphasized and specific recommendations for the monetary policy will be formulated.

Chapter 2

Literature review

In this section I will briefly summarize the main findings concerning the financial crises and financial frictions modelling published in the literature. I will also mention the most significant references concerning the structural changes.

2.1 Research of economic crises

Prior to the financial and economic crisis of 2007–2009 the economic research of such crises mainly concentrated on the Great Depression of 1930s. Here I would mention a work of Bernanke (1983) who studied the turmoil in the financial sector during the Great Depression and its effects on the rest of the economy. He concluded that the downturn in investment was caused by several factors. Bankruptcies of established financial institutions led to overall decrease in the quality of financial services and an increase in the costs of credit intermediation, which discouraged a part of potential investors. Also, banks remaining in business perceived increased risks and offered new loans quite reluctantly, which means that more applicants for loans were rejected because they were not considered creditworthy by the banks. And finally, fall in the value of assets during the crisis rendered many potential investors unable to put up suitable collateral for their desired loans. Even though the analysis concerns the Great Depression, surprisingly many observations are relevant for the recent crisis.

Another interesting publication that studies the financial crises in a broader perspective is Kindleberger and Aliber (2011). This publication offers thorough analysis of the most important financial crises from the Dutch Tulip Bulb Bubble of 1636 to the dot.com bubble of late 1990s, it describes the anatomy of a typical financial crisis and describes suitable policy responses.

Reinhart and Rogoff (2009) study 18 major financial crises that occurred in the developed world after the World War II. They find that, on average, the financial crises cause a prolonged decline of real housing prices (35 % decline over 6 years) as well as of the equity prices (55 % decline over 3.5 years). Also, the theoretical average financial crisis would cause the unemployment rate to rise 7 percentage points (over 4 years), the real output to decline 9 % (over 2 years) and the government debt to rise 86 %.

2.2 Financial and economic crisis of 2007–2009

The development of current financial and economic crisis of 2007–2009 is described and analysed for example by Krishnamurthy (2010). In this paper, main factors that influence the decision making process of agents participating on the debt market are examined in detail. Author finds that a negative systemic shock together with high leverage caused a huge decline in the equity capital of the financial intermediaries during the crisis, which made the financial institutions more risk-averse and the debt market less liquid. Also, Repo financing was effectively curtailed by high haircuts[1] required by the hedge funds because of high risk of default and declining value of collateral in that period. As the debt market became illiquid the demand moved towards short-term financing facilities, arbitrage began to fail and fundamental prices diverged from market prices. In those circumstances the policy interest rates were not directly reflected by the debt market and, thus, the situation improved only gradually when the government provided additional liquidity and the confidence slowly returned.

Similarly to the previous paper, Mishkin (2010) describes the events of the crisis quite thoroughly. The author shows how increased uncertainty and bankruptcy risk together with falling prices of collateral led to freezing of the debt market that was rendered unable to allocate available resources to suitable candidates. The paper than focuses on the monetary policy intervention that took mainly the form of quantitative easing (liquidity provision and asset purchases) but non-conventional monetary policy was also applied (management of expectations).

In Mishkin (2009), the author argues that the conventional monetary policy was still being effective during recent crisis even though the spreads[2] increased substantially. In short, the author claims that the market rates would have been even higher if the policy interest rates had not been lowered.

Finally, Mishkin (2011) summarizes the most important facts we have learned from the crisis. Current crisis showed how very important is the financial sector for the economic activity. We found that price and output stability does not ensure financial stability. And we also observed the very high clean-up costs of the financial crisis.

2.3 Model based analysis of financial frictions

There are three main financial frictions mechanisms: cash-flow constraints, collateral constraints and financial regulations, which is reflected in different approaches to the financial frictions modelling.

It was Bernanke et al. (1999) who introduced the financial accelerator mechanism into the New Keynesian DSGE framework. In their concept, a firm's balance sheet effects together with costly state verification give rise to the external finance premium that is paid extra by the borrowers on top of the opportunity cost of internal funds and acts as a cash-flow constraint. External finance premium behaves counter-cyclically and thus amplifies the effects of exogenous shocks. Christensen and Dib (2008) further extended the original concept by rewriting the debt contracts in nominal terms to better reflect reality and they included money-growth in the Taylor rule in order to better model the monetary policy.

Financial frictions can be also introduced into the DSGE model by linking the creditworthiness of the borrowers to the value of their assets. This idea was introduced by Kiyotaki and Moore (1997), who presented a theoretical model with collateral constraints, where the overall size of the debt that borrowers can obtain is limited by the value of their

[1]Haircut is a share of the total value of the transaction that has to be paid by the borrower, the rest is paid by the lender.

[2]Spread of the policy interest rate and the market rates generally.

assets. Thus, a negative shock that causes a decline of the value of collateral leads to a restriction of the firm's borrowing and consequently a reduction of investment and consumption. Nominal debt contracts and real estate demand were introduced by Iacoviello (2005).

The third way of financial frictions modelling is oriented at explaining specific features of the financial crises that take place on the supply side of the financial markets. Edwards and Végh (1997) proposed explicit banking sector modelling with banking services modelled as costly services. A DSGE model with explicit banking sector was introduced by Goodfriend and McCallum (2007), where the commercial banks maximize their profits given the loans production technology and demand for deposits and loans. The bank's production function takes collateral and labour as inputs, as the labour is used to perform the loan monitoring. Cúrdia and Woodford (2009) presented a stylized model with explicit banking sector and heterogeneous households.

2.4 Recent development in financial frictions modelling

Recent financial and economic crisis sparked new interest in the research of financial frictions especially among the central bankers but also among academic researchers. Several interesting studies comparing and contrasting the different ways of financial frictions modelling within the DSGE framework were produced since 2008. Namely, I would mention Arend (2010) and Quadrini (2011), Brzoza-Brezina et al. (2011) and Brzoza-Brzezina and Kolasa (2012) from the National Bank of Poland. A comprehensive review of literature related to the financial frictions in DSGE models can be found in Brázdik et al. (2012). The survey summarizes the development of the main theoretical approaches to financial frictions modelling from the seminal publications to recent extensions.

Another wide group of papers describes applications of particular DSGE models on recent crisis. The volume of this research is quite impressive and it is still increasing to this day as the research of financial frictions continues. These papers usually focus on the situation in the U.S. but there are some exceptions.[3] Adrian et al. (2012) observe five stylized facts about the financial sector, formulate a model of direct and intermediated credit and propose its incorporation in a general equilibrium framework. Hall (2010) and (2011) studies two kinds of financial frictions, one that affects rental cost of capital to firms and the other affects the rental cost of housing and durable goods. Author concludes that the financial frictions are important determinants of the business cycle.

Christensen and Dib (2005) and (2008) estimate a sticky-price DSGE model with the financial accelerator and find that the model without the financial frictions is statistically rejected in favor of model with it. The authors also find that the importance of the financial accelerator for output fluctuations is rather minor. Dib (2010) develops a DSGE model with active banking sector, financial accelerator and financial frictions in the interbank and bank capital markets and finds that the financial frictions amplify and propagate the shocks while the capital requirement moderates impacts of exogenous shocks. Hafstead and Smith (2012) build a DSGE model with financial accelerator and monopolistically competitive banking sector. The paper focuses on the costs and benefits of bank intermediation and shows large macroeconomic effects of different demand and supply shocks originating in the financial sector on the real economic activity. Rychalovska (2010) uses a DSGE model with financial accelerator to study how alternative assumptions about the formation of expectations affect the implications of the financial frictions for the real econ-

[3] These exceptions are distinguished explicitly in following text.

omy. Gertler et al. (2012) develop a DSGE model with financial intermediation where banks issue outside equity as well as short term debt to study the causes of financial sector vulnerability.

Chrisitano et al. (2011) include the financial accelerator mechanism into the medium-sized DSGE model with search and matching frictions for the Swedish economy and they find that the financial shock is crucial for explaining the fluctuations in investment and GDP. Dedola and Lombardo (2012) construct a two-country DSGE model with financial accelerator for the euro area and the U.S. to study the effects of leverage of the investors and find that the increased spreads can globally propagate to other financially integrated countries. Kolasa and Lombardo (2011) use a DSGE model with financial accelerator for the euro area to study the welfare effects of financial frictions and find that the welfare losses are non-negligible. Deák et al. (2012) incorporate the banking sector into a small open economy DSGE model for the Luxembourg economy where the financial sector plays very important role.

The role of financial frictions in the Czech economy was investigated for example in Ryšánek et al. (2012). The authors used a DSGE model based on Christiano et al. (2011) and found that the monetary policy response implied by the model with financial frictions was amplified by increased spread. Tonner and Vašíček (2011) arrived to similar outcome. According to their results, the monetary policy would be more aggressive in terms of policy rate cut if the financial frictions were considered. Tvrz (2012) and Tvrz and Vašíček (2012) estimated a DSGE model with financial accelerator and found evidence of financial frictions effects during recent crisis. The effects of financial frictions in the Polish economy were studied by Brzoza-Brzezina and Kolasa (2013) or Brzoza-Brzezina *et al.* (2013). The repercussions of the shocks originating in the financial sector in the Hungarian economy were explored by Tamási and Világi (2011).

2.5 Structural stability of the economic system

The question of structural stability of the macroeconomic system was investigated by Fernández-Villaverde and Rubio-Ramirez (2007). The authors studied the stability of structural parameters of a medium-scale non-linear DSGE model of the U.S. economy that allowed parameter drifting. Identified changes in the pricing behaviour of firms and households captured by respective Calvo parameters were the most pronounced. Kulish and Pagan (2013) developed solutions for linearised DSGE models with structural changes that economic agents have various kinds of beliefs about. Yano (2010) proposed a new method of studying time-varying structural parameters with the use of Sequential Monte Carlo methods. The author assessed the stability of the structural parameters of a DSGE model of the U.S. economy and identified the most important changes in their values. Justiniano and Primiceri (2008) studied the changes in the volatility of the exogenous shocks in the period of Great Moderation with the use of a DSGE model of the U.S. economy.

The subject of the structural stability of the small Central European economies has been investigated for example by Vašíček *e*t al. (2011), who found evidence of parameter drifting in the Czech data, or by Čapek (2012), who compared a recursive estimation approach to non-linear filtration. Structural stability of the remaining Visegrád economies has been less fully investigated. Structural differences in the labour market of the four Visegrád countries were investigated by Němec (2013).

Chapter 3

Model

In this chapter, a dynamic stochastic model of general equilibrium (DSGE model) of a small open economy (SOE) with financial frictions is described. The model framework follows Shaari (2008), who enhanced the basic small open economy framework proposed by Galí (1999) and Galí and Monacelli (2005) with the financial accelerator mechanism as described in Bernanke *et al.* (1999). In this thesis, I elaborated on the model that was implemented in Tvrz (2012). The model structure was adjusted in order to allow time-varying structural parameters. In case of the Slovak economy, monetary policy regime switch was introduced into the model to deal with the euro adoption in 2009. Several changes were made to the original concept of Shaari (2008). Foreign variables are modelled with the use of vector autoregression model (VAR) of order one. This enables us to impose more structure on the behaviour of foreign variables and to identify the foreign exogenous shocks better than with independent AR(1) processes. Also, exogenous shock in entrepreneurs' net worth was introduced into the model.

Used notation is summarized in appendix A. Derivation of most of the model equations is presented in the thesis. However, some more space-consuming derivations were removed from this chapter to make it more concise. These derivations can be found in the appendix B. In this chapter, only the definitions and important results will be presented.

3.1 Definitions

3.1.1 Consumption demand and price indices

Consumption index C_t is defined as

$$C_t = \left[(1-\gamma)^{\frac{1}{\eta}}(C_{H,t})^{\frac{\eta-1}{\eta}} + \gamma^{\frac{1}{\eta}}(C_{F,t})^{\frac{\eta-1}{\eta}}\right]^{\frac{\eta}{\eta-1}}, \tag{3.1.1}$$

where γ measures openness of the domestic economy and η is the elasticity of substitution between home and foreign goods. Subscripts H and F denote the country of origin, which means that the consumption index is composed of home and foreign goods.

Home goods consumption index is defined as

$$C_{H,t} = \left(\int_0^1 C_{H,t}(h)^{\frac{\varepsilon-1}{\varepsilon}}\,\mathrm{d}h\right)^{\frac{\varepsilon}{\varepsilon-1}}, \tag{3.1.2}$$

with elasticity of substitution between different varieties of goods ε. There is a continuum of home goods varieties. The demand function for particular variety of home goods[1] can

[1] The derivation of this result can be found in the appendix B, section B.1.1.

be expressed as

$$C_{H,t}(j) = C_{H,t} \left(\frac{P_{H,t}(j)}{P_{H,t}} \right)^{-\varepsilon}. \tag{3.1.3}$$

The home goods price index is defined as

$$P_{H,t} = \left(\int_0^1 P_{H,t}(i)^{1-\varepsilon} \, \mathrm{d}i \right)^{\frac{1}{1-\varepsilon}}. \tag{3.1.4}$$

Foreign goods consumption index definition is analogous to the definition of home goods index (3.1.2). Therefore, also the demand function for particular variety of foreign goods and foreign goods price index are analogous to (3.1.3) and (3.1.4).

The consumer price index (CPI) P_t is defined as

$$P_t = \left[(1-\gamma) P_{H,t}^{1-\eta} + \gamma P_{F,t}^{1-\eta} \right]^{\frac{1}{1-\eta}}. \tag{3.1.5}$$

The demand of households for home and foreign goods[2] is given by following functions:

$$C_{H,t} = C_t (1-\gamma) \left(\frac{P_{H,t}}{P_t} \right)^{-\eta}, \tag{3.1.6}$$

$$C_{F,t} = C_t \gamma \left(\frac{P_{F,t}}{P_t} \right)^{-\eta}. \tag{3.1.7}$$

3.1.2 Inflation

A standard definition of CPI inflation is assumed[3]

$$\pi_t = \log \left(\frac{P_t}{P_{t-1}} \right) = p_t - p_{t-1}. \tag{3.1.8}$$

Analogously we define the inflation of home goods prices $\pi_{H,t}$, inflation of foreign goods prices $\pi_{F,t}$ and foreign[4] CPI inflation π_t^*. Note that all the price indices are assumed to be equal to one in steady state. Log-linearization[5] of price index definition (3.1.5) gives this result

$$p_t = (1-\gamma) p_{H,t} + \gamma p_{F,t}, \tag{3.1.9}$$

which implies

$$\pi_t = (1-\gamma) \pi_{H,t} + \gamma \pi_{F,t}. \tag{3.1.10}$$

3.1.3 Terms of trade

The terms of trade, TOT_t, are defined as

$$TOT_t = \frac{P_{F,t}}{P_{H,t}}.$$

This variable measures the relative price of foreign and home goods and it is expressed in domestic currency. Since $tot_t = p_{F,t} - p_{H,t}$, it can be shown that $p_t = p_{H,t} - \gamma tot_t$ and $\pi_t = \pi_{H,t} + \gamma \Delta tot_t$.

[2] The derivation of this result can be found in the appendix B, section B.1.2.

[3] The logarithmic deviations from steady state are denoted by small letter variables, i.e. $\log \left(\frac{X_t}{X} \right) = x_t$.

[4] Foreign variables are denoted by an asterisk.

[5] The model equations are log-linearized around the deterministic steady state. Log-linear equations are, therefore, only approximations of true behaviour of model economy. Nevertheless, in the vicinity of the steady state the approximation error is negligible.

3.1.4 Real exchange rate

Denote S_t the nominal interest rate in direct quotation (CZK/EUR). Thus, growth of S_t means a depreciation of domestic currency and vice versa. The real exchange rate, RER_t, is then defined as

$$RER_t = S_t \frac{P_t^*}{P_t},$$

where P_t^* is foreign CPI index.

3.1.5 Law of one price gap

We suppose that law of one price holds for domestic[6] exports, $C_{H,t}^*$, i.e.

$$P_{H,t}^* = \frac{P_{H,t}}{S_t}.$$

However, this is not the case for domestic imports, or foreign goods. We assume that there is a wedge between the price of foreign goods in the domestic economy and the price level of foreign country, this means that the law of one price does not hold for the imported goods. We define a law of one price gap

$$LOP_t = \frac{S_t P_t^*}{P_{F,t}}.$$

In log-linear terms $lop_t = s_t + p_t^* - p_{F,t}$. It can be shown that following relation holds for real exchange rate, terms of trade and law of one price gap

$$rer_t = (1-\gamma) tot_t + lop_t. \tag{3.1.11}$$

The development of the law of one price gap is exogenous in this model and its deviation from steady state is assumed to follow AR(1) process of following form

$$lop_t = \rho_{LOP} lop_{t-1} + \varepsilon_t^{LOP},$$

where $\rho_{LOP} \in \langle 0, 1 \rangle$ is the AR(1) coefficient and the innovation term $\varepsilon_t^{LOP} \sim iid(0, \sigma_{LOP}^2)$.

3.2 Households

Households maximize expected discounted sum of utilities by choosing optimal consumption and labour paths and solve following optimization problem

$$\max_{\{C_t, L_t\}_{t=0}^{\infty}} E_0 \left\{ \sum_{t=0}^{\infty} \beta^t U(C_t, C_{t-1}, L_{H,t}) \right\}$$

subject to a budget constraint. $\beta \in \langle 0, 1 \rangle$ is exogenous discount parameter. Following functional form of utility function is assumed

$$U(C_t, L_t) = \log(C_t - \Upsilon C_{t-1}) - \frac{L_{H,t}^{1+\Psi}}{1+\Psi},$$

[6]Subscript H and F indicates always the country of origin. Therefore, $C_{H,t}^*$ denotes goods produced in domestic economy but consumed abroad.

where C_t is consumption index, $L_{H,t}$ is household's labour supply, Υ is the parameter of external habit and Ψ is inverse elasticity of labour supply.

The budget constraint of representative household has following form

$$\widetilde{W}_{H,t} L_{H,t} + R_{t-1} D_{t-1} + R^*_{t-1} \Psi^B (Z_{t-1}, A^{UIP}_{t-1}) S_t B_{t-1} + \Pi^r_t + TR_t = P_t C_t + D_t + S_t B_t.$$

This means that the household gets remuneration for provided amount of labour $L_{H,t}$ in a form of nominal[7] wage $\widetilde{W}_{H,t}$. Also, the household receives profits from retail firms Π^r_t and left-over equity of entrepreneurs that go bankrupt and leave the economy in a form of transfers TR_t.

The representative household spends its income on consumption but they can also buy two kinds of assets: domestic bonds D_t from domestic intermediary and foreign bonds B_t (denominated in foreign currency). Domestic bonds yield nominal interest rate R_t in one period. Foreign bonds yield risk-adjusted[8] return $R^*_t \Psi^B(Z_t, A^{UIP}_t)$ in one period. Risk-premium is specified according to Adolfson *et al.* (2008) as

$$\Psi^B(Z_t, A^{UIP}_t) = \exp\left[-\psi^B(Z_t + A^{UIP}_t)\right],$$

where R^*_t is foreign nominal interest rate, $Z_t = \frac{S_t B_t}{Y_{H,t} P_{H,t}}$ is the net foreign assets position of the domestic economy and A^{UIP}_t is the debt-elastic risk premium shock.[9] Deviation of this shock from steady state is assumed to follow AR(1) process of standard form

$$a^{UIP}_t = \rho_{UIP} a^{UIP}_{t-1} + \varepsilon^{UIP}_t,$$

where $\rho_{UIP} \in \langle 0, 1\rangle$ and the innovation term $\varepsilon^{UIP}_t \sim iid(0, \sigma^2_{UIP})$. The solution of house-

[7]Nominal variables are denoted by tilde, i.e. $\widetilde{X}_t = X_t P_t$.

[8]Risk-adjustment is introduced into the model in order to stationarize the net foreign assets position in the steady state. See Schmitt-Grohé and Uribe (2003) for detailed explanation.

[9]Since it directly influences the development of real exchange rate via uncovered interest parity condition (UIP condition), it is denoted as UIP shock.

holds' optimization problem[10] can be summarized by following optimality conditions:

- Optimal choice between consumption and free time:

$$\frac{\widetilde{W}_{H,t}}{P_t} = W_{H,t} = L_{H,t}^{\psi}(C_t - \Upsilon C_{t-1}). \tag{3.2.1}$$

- Optimal choice between consumption and domestic bonds is given by:

$$R_t = \frac{1}{\beta} \frac{C_{t+1} - \Upsilon C_t}{C_t - \Upsilon C_{t-1}} \frac{P_{t+1}}{P_t}. \tag{3.2.2}$$

- Optimal choice between consumption and foreign bonds:

$$R_t^* \Psi^B(Z_t, A_t^{UIP}) = \frac{1}{\beta} \frac{S_t}{S_{t+1}} \frac{(C_{t+1} - \Upsilon C_t)}{(C_t - \Upsilon C_{t-1})} \frac{P_{t+1}}{P_t} \tag{3.2.3}$$

- Optimal choice between foreign and domestic bonds:

$$\begin{aligned} R_t^* \Psi^B(Z_t, A_t^{UIP}) &= \frac{S_t}{S_{t+1}} R_t, \\ R_t^* \exp\left[-\psi^B(Z_t + A_t^{UIP})\right] &= R_t \frac{RER_t P_t}{P_t^*} \frac{P_{t+1}^*}{P_{t+1} RER_{t+1}}, \end{aligned} \tag{3.2.4}$$

  which is a risk-adjusted uncovered interest parity (UIP) condition.

In log-linear terms we can write:

$$l_{H,t} = \frac{w_{H,t}}{\Psi} - \frac{c_t - \Upsilon c_{t-1}}{\Psi(1 - \Upsilon)} \tag{3.2.5}$$

$$(1 - \Upsilon)(r_t - E_t \pi_{t+1}) = (c_{t+1} - \Upsilon c_t) - (c_t - \Upsilon c_{t-1}) \tag{3.2.6}$$

$$rer_{t+1} - rer_t = (r_t - E_t \pi_{t+1}) - (r_t^* - E_t \pi_{t+1}^*) + \psi^B z_t + \psi^B a_t^{UIP} \tag{3.2.7}$$

3.3 Entrepreneurs

Following Bernanke *et al.* (1999), we next introduce a production factor of capital into the model and describe the entrepreneur as a representative economic agent. Entrepreneurs play two important roles in the model. Firstly, they own and manage firms that produce intermediate (wholesale) goods and, secondly, they own and produce the capital goods.

In owning and production of capital goods the entrepreneurs face a financing constraint. This means that the entrepreneurs are not fully self-financing, and therefore, they have to borrow resources from commercial banks. The banks always demand higher interest rate than the policy interest rate. The spread between commercial interest rate and policy interest rate is determined by the ratio of the value of capital stock and entrepreneurs' net worth (leverage ratio). What we have just described is the financial accelerator mechanism and it is the source of financial frictions in this model.

To rule out the possibility that the entrepreneurs could accumulate enough net worth to become fully self-financing, the entrepreneurs have to have a finite horizon. For that purpose it is assumed that a fraction $\varsigma \in \langle 0, 1 \rangle$ of entrepreneurs goes bakrupt each period in steady state. Remaining share $(1 - \varsigma)$ of entrepreneurs survives to the next period.

[10] The derivation of these results can be found in the appendix B, section B.2.

3.3.1 Intermediate goods production

Firms that produce intermediate goods operate at perfectly competitive market. This means that these firms have no market power and will attain no profits. Intermediate goods $Y_{H,t}$ is produced by combining the production factors of capital K_t and labour L_t. The output is sold at wholesale price $P_{H,t}^{W}$ to retailers. Standard Cobb-Douglas production technology is assumed,

$$Y_{H,t} = A_t^Y K_t^{\alpha} L_t^{1-\alpha},$$

where parameter $\alpha \in \langle 0, 1 \rangle$ determines the income share of capital. A_t^Y is a productivity shock; its deviation from steady state is assumed to evolve according to following AR(1) process

$$a_t^Y = \rho_Y a_{t-1}^Y + \varepsilon_t^Y,$$

where $\rho_Y \in \langle 0, 1 \rangle$ and $\varepsilon_t^Y \sim iid(0, \sigma_Y^2)$. The total labour input is defined as a composite of the labour provided by households $L_{H,t}$ and by entrepreneurs $L_{E,t}$,

$$L_t = L_{H,t}^{\Omega} L_{E,t}^{1-\Omega}.$$

In line with Bernanke *et al.* (1999) we normalize the labour input of entrepreneurs to 1. The production function can be then rewritten as

$$Y_{H,t} = A_t^Y K_t^{\alpha} L_{H,t}^{\Omega(1-\alpha)},$$

or in log-linear terms

$$y_{H,t} = \alpha k_t + (1-\alpha)\Omega l_{H,t} + a_t^Y. \tag{3.3.1}$$

The solution of entrepreneurs' optimization problem[11] can be summarized by following set of optimality conditions:

$$\begin{aligned}
\frac{\widetilde{R}_{G,t}}{P_t} &= R_{G,t} = \alpha \frac{Y_{H,t}}{K_t} MC_{H,t} \frac{P_{H,t}}{P_t}, \\
\frac{\widetilde{W}_{H,t}}{P_t} &= W_{H,t} = \Omega(1-\alpha) \frac{Y_{H,t}}{L_{H,t}} MC_{H,t} \frac{P_{H,t}}{P_t}, \\
\frac{\widetilde{W}_{E,t}}{P_t} &= W_{E,t} = (1-\Omega)(1-\alpha) Y_{H,t} MC_{H,t} \frac{P_{H,t}}{P_t},
\end{aligned}$$

where $\widetilde{R}_{G,t}$ is the gross nominal rental rate for capital, $\widetilde{W}_{H,t}$ is the nominal wage paid to households, $\widetilde{W}_{E,t}$ is the nominal wage paid to entrepreneurs themselves and $MC_{H,t}$ are the real marginal costs of home goods production. After log-linearization we receive[12]

$$r_{G,t} = y_{H,t} + mc_{H,t} - k_t - \left[\frac{\gamma}{1-\gamma}(rer_t - lop_t)\right], \tag{3.3.2}$$

$$w_{H,t} = y_{H,t} + mc_{H,t} - l_{H,t} - \left[\frac{\gamma}{1-\gamma}(rer_t - lop_t)\right], \tag{3.3.3}$$

$$w_{E,t} = y_{H,t} + mc_{H,t} - \left[\frac{\gamma}{1-\gamma}(rer_t - lop_t)\right].$$

[11] The derivation of these results can be found in the appendix B, section B.3.1.

[12] We used the equation (3.1.11) and relations described in sections 3.1.2 and 3.1.3.

Plugging for k_t and $l_{H,t}$ from (3.3.2) and (3.3.3) into the production function (3.3.1) we receive the expression for real marginal costs,

$$mc_{H,t} = \frac{(1-\alpha)(1-\Omega)y_{H,t} + \alpha r_{G,t} + (1-\alpha)\Omega w_{H,t} - a_t^Y}{\alpha + (1-\alpha)\Omega} + \frac{\gamma}{1-\gamma}(rer_t - lop_t). \quad (3.3.4)$$

Equation (3.3.4), therefore, suggests that depreciation of the real exchange rate increases the real marginal costs while an increase of law of one price gap decreases them.

3.3.2 Capital goods production

Entrepreneurs produce capital goods and sell it at competitive market at nominal price $\widetilde{Q}_t$. Capital is produced by combining already existing capital with investment INV_t. Investment INV_t is a bundle of home and foreign consumption goods. We assume, that the entrepreneurs choose the optimal mix of goods varieties in the same way as the households. Therefore, the investment is defined analogously to the the consumption index C_t in equation (3.1.1),

$$INV_t = \left[(1-\gamma)^{\frac{1}{\eta}}(C_{H,t})^{\frac{\eta-1}{\eta}} + \gamma^{\frac{1}{\eta}}(C_{F,t})^{\frac{\eta-1}{\eta}}\right]^{\frac{\eta}{\eta-1}}. \quad (3.3.5)$$

Thus, the demand of entrepreneurs for home and foreign goods as well as respective price indices are the same as in the case of households.

Stock of capital goods is assumed to evolve according to

$$K_{t+1} = \Phi\left(\frac{INV_t}{K_t}\right)K_t + (1-\delta)K_t, \quad (3.3.6)$$

where $\delta \in \langle 0, 1\rangle$ is the rate of capital depreciation and $\Phi(.)$ is an increasing concave production function. Following functional form is assumed for $\Phi(.)$

$$\Phi\left(\frac{INV_t}{K_t}\right) = \frac{INV_t}{K_t} - \frac{\psi^I}{2}\left(\frac{INV_t}{K_t} - \delta\right)^2,$$

where $\psi^I > 0$ is the capital adjustment costs parameter. Following Bernanke *et al.* (1999), the capital adjustment costs are introduced into the model to allow movement in the price of capital, which increases the volatility in entrepreneurs' net worth and contributes to the financial accelerator effect.

In the steady state,[13] the production function has following properties: $\Phi\left(\frac{\overline{INV}}{\overline{K}}\right) = \delta$, $\Phi'\left(\frac{\overline{INV}}{\overline{K}}\right) = 1$. These properties ensure deterministic level of capital stock in the steady state (investment only replaces depreciated capital, $\overline{INV} = \delta\overline{K}$) and also that the price of capital will be equal to one in the steady state ($\overline{Q} = 1$). Therefore, log-linearizing the law of motion of capital (3.3.6) gives[14]

$$k_{t+1} = \delta inv_t + (1-\delta)k_t.$$

The entrepreneur decides about how much new capital to produce. The optimality condition is[15]

$$Q_t = \frac{1}{1 - \psi^I\left(\frac{INV_t}{K_t} - \delta\right)},$$

[13] We denote steady state values of all variables by overline.

[14] The derivation of this result can be found in the appendix B, section B.3.2.

[15] The derivation of this result can be found in the appendix B, section B.3.2.

which in log-linear terms means

$$q_t = \psi^I \delta(i_t - k_t). \tag{3.3.7}$$

Now we define entrepreneur's gross real return on capital investment $R_{K,t}$,

$$R_{K,t} = \frac{[R_{G,t} + (1-\delta)Q_t]K_t}{Q_{t-1}K_t}.$$

In log-linear terms we receive

$$r_{K,t} = \left(1 - \frac{1-\delta}{\overline{R}_K}\right) r_{G,t} + \frac{1-\delta}{\overline{R}_K} q_t - q_{t-1} \tag{3.3.8}$$

Utilization of capital in production of intermediate goods yields gross real rental rate $R_{G,t}$. Since the entrepreneurs own the capital, any change in the price of capital also influences the return on investment and consequently it affects the entrepreneur's net worth.

3.3.3 Financial frictions

Entrepreneurs finance their capital investment projects using their net worth N_{t+1} and borrowed funds F_{t+1}. Thus, the entrepreneurs' budget constraint can be written down as

$$Q_t K_{t+1} = N_{t+1} + F_{t+1},$$

or in log-linear terms

$$\overline{K}(q_t + k_{t+1}) = \overline{N} n_{t+1} + \overline{F} f_{t+1}. \tag{3.3.9}$$

When borrowing from financial intermediary, entrepreneur has to pay not only the gross real interest rate $R_t \frac{P_t}{P_{t+1}}$, but also the external finance premium, EFP_{t+1}. This premium depends on the leverage ratio of the entrepreneur and it is defined as

$$EFP_{t+1} = \left(\frac{N_{t+1}}{Q_t K_{t+1}}\right)^{-\chi},$$

where $\chi > 0$ is the elasticity of the external finance premium with respect to the leverage ratio $\frac{N_t}{Q_{t-1}K_t}$. Bernanke *et al.* (1999) motivate this set-up by an agent-principal problem at the credit market.

Entrepreneurs are risk-neutral and choose K_{t+1} to maximize profits. The amount of borrowed funds F_{t+1} is implied by chosen K_{t+1}. To maximize the profits, entrepreneurs equate expected marginal return on capital investment with marginal financing costs

$$E_t R_{K,t+1} = E_t \left[\left(\frac{N_{t+1}}{Q_t K_{t+1}}\right)^{-\chi} R_t \frac{P_t}{P_{t+1}}\right], \tag{3.3.10}$$

which again in log-linear terms gives

$$E_t r_{K,t+1} = r_t - E_t \pi_{t+1} - \chi(n_{t+1} - q_t - k_{t+1}).$$

Now we derive the evolution of entrepreneurs' net worth. The new net worth consists of entrepreneurial equity held by the fraction $(1-\varsigma)A_t^{NW}$ of entrepreneurs that will survive current period and entrepreneurs' wage income $W_{E,t}$,

$$N_{t+1} = (1-\varsigma)A_t^{NW} V_t + W_{E,t}, \tag{3.3.11}$$

where A_t^{NW} is shock in entrepreneurial net worth and ς is the steady-state bankruptcy rate. Thus, the net worth shock influences the development of net worth by changing the effective survival rate of entrepreneurs. Its deviation from steady state is assumed to evolve according to AR(1) process,

$$a_t^{NW} = \rho_{NW} a_{t-1}^{NW} + \varepsilon_t^{NW},$$

where $\rho_{NW} \in \langle 0, 1 \rangle$ and $\varepsilon_t^{NW} \sim iid(0, \sigma_{NW}^2)$.

The remaining entrepreneurs who leave the economy transfer their equity to households as transfers $TR_t = \varsigma A_t^{NW} V_t$. This mechanism ensures that net worth is pinned down in steady state. We also assume that labour income of entrepreneurs is small ($1 - \Omega = 0.01$). Wage income of entrepreneurs ensures, that they always have positive net worth to do the business with. Entrepreneurs' equity is defined as

$$V_t = R_{K,t} Q_{t-1} K_t - \left(\frac{N_t}{Q_{t-1} K_t} \right)^{-\chi} R_{t-1} \frac{P_{t-1}}{P_t} F_t. \tag{3.3.12}$$

Thus, the entrepreneurs' equity is the realized return on capital investment minus the repayment of loans. Note that an increase in interest rate lowers entrepreneurs' net worth, which increases the premium and further lowers the net worth.

To obtain a log-linear approximation of entrepreneurial net worth dynamics in the neighbourhood of steady state, we log-linearize the entrepreneurial equity definition and rearrange to receive[16]

$$\begin{aligned} n_{t+1} = (1 - \varsigma) \overline{R}_K & \left[(\Gamma + 1) r_{K,t} - \chi \Gamma (q_{t-1} + k_t) - \Gamma (r_{t-1} - \pi_t) + (\chi \Gamma + 1) n_t + a_t^{NW} \right] + \\ & + (\Gamma + 1) \frac{\overline{W}_E}{\overline{K}} w_{E,t}, \end{aligned} \tag{3.3.13}$$

where we used this substitution: $\frac{\overline{K} - \overline{N}}{\overline{N}} = \Gamma$, $\frac{\overline{K}}{\overline{N}} = \Gamma + 1$ and $\frac{\overline{W}_E}{\overline{N}} = \frac{\overline{W}_E}{\overline{K}} \frac{\overline{K}}{\overline{N}} = (\Gamma + 1) \frac{\overline{W}_E}{\overline{K}}$.

3.4 Retailers

There are two types of retailers in the model economy. Home goods retailers buy intermediate goods from entrepreneurs and sell it as home goods to households or export it abroad. Foreign goods retailers buy final goods abroad and sell it to the households as foreign goods. Both types of retailers operate at monopolistically competitive markets. Thus, the retailers have certain market power and earn non-zero profits. These profits are distributed back to households. The retailers are assumed to practice Calvo-type price setting with inflation indexation, which means that there are nominal price rigidities in the model.

3.4.1 Home goods retailers

Home goods retailers buy the intermediate good from entrepreneurs at the wholesale price $P_{H,t}^W$ and at no additional costs they distribute the home goods to the households. Price of retailer z is denoted by $P_{H,t}(z)$, $z \in \langle 0, 1 \rangle$. Each period, only a fraction $(1 - \theta_H)$ of retailers reset their prices to new optimal price $P_{H,t}^{NEW}$. Since all the home goods retailers face the same optimization problem, the new optimal price is common to all of them.

[16] The derivation of this result can be found in the appendix B, section B.3.3.

The remaining fraction of the home goods retailers θ_H adjust their price according to last period CPI inflation according to

$$P_{H,t}(z) = P_{H,t-1}(z)(\pi_{t-1})^{\kappa},$$

where $\kappa \in \langle 0, 1 \rangle$ measures the degree of inflation indexation. Together with (3.1.4) this implies aggregate price level of home goods

$$P_{H,t} = \left[(1-\theta_H)\left(P_{H,t}^{NEW}\right)^{1-\varepsilon} + \theta_H \left(P_{H,t-1}(\pi_{t-1})^{\kappa}\right)^{1-\varepsilon}\right]^{\frac{1}{1-\varepsilon}},$$

or in log-linear terms

$$p_{H,t} = (1-\theta_H)p_{H,t}^{NEW} + \theta_H p_{H,t-1} + \theta_H \kappa \pi_{t-1} \tag{3.4.1}$$

The Calvo parameter θ_H measures the rigidity of home goods prices. It is an exogenous probability of keeping current price of any particular home good for the next period without any change. It can be shown that the expected duration of any particular home good price is given by $\frac{1}{1-\theta_H}$.

The Phillips curve of home goods is given by[17]

$$\pi_{H,t} = \beta E_t \pi_{H,t+1} - \kappa\beta\pi_t + \kappa\pi_{t-1} + \frac{(1-\theta_H)(1-\theta_H\beta)}{\theta_H} mc_{H,t}. \tag{3.4.2}$$

3.4.2 Foreign goods retailers

Foreign goods retailers buy the final goods abroad and sell it to the households at price $P_{F,t}$. Law of one price is assumed to hold at the wholesale level. Therefore, the foreign goods retailers buy the goods at a price $P_{F,t}^W = S_t P_t^*$. Since the law of one price does not hold at retail level ($P_{F,t} \neq S_t P_t^*$), the effect of the incomplete exchange rate pass-through is introduced into the model. Similarly to the home goods retailers, the foreign goods retailers set their prices à la Calvo with parameter θ_F and inflation indexation with parameter κ.

To obtain the log-linear approximation of the foreign goods inflation dynamics in the neighbourhood of the steady state, we would have to proceed the same way as in the section B.4.1. However, all the results presented in the section 3.4.1 are valid also for foreign goods retailers. Only the subscript H has to be changed to F everywhere it appears. Therefore, we can write

$$\pi_{F,t} = \beta E_t \pi_{F,t+1} - \kappa\beta\pi_t + \kappa\pi_{t-1} + \frac{(1-\theta_F)(1-\theta_F\beta)}{\theta_F} mc_{F,t}.$$

Unlike in the section 3.4.1, here we can proceed a bit further and use the fact that $MC_{F,t} =$
$= \frac{P_{F,t}^W}{P_{F,t}} = \frac{S_t P_t^*}{P_{F,t}}$, and therefore, $mc_{F,t} = s_t + p_t^* - p_{F,t} = lop_t$ to obtain the final form of foreign goods Phillips curve,

$$\pi_{F,t} = \beta E_t \pi_{F,t+1} - \kappa\beta\pi_t + \kappa\pi_{t-1} + \frac{(1-\theta_F)(1-\theta_F\beta)}{\theta_F} lop_t. \tag{3.4.3}$$

[17] The derivation of this result can be found in the appendix B, section B.4.1.

3.4.3 CPI inflation

Finally, we will derive the log-linear approximation of CPI inflation dynamics. Plugging the results (3.4.2) and (3.4.3) into the definition of CPI inflation (3.1.10) we obtain

$$\pi_t = \frac{1}{1+\kappa\beta}\left[\beta E_t\pi_{t+1} + \kappa\pi_{t-1} + (1-\gamma)\Lambda_H mc_{H,t} + \gamma\Lambda_F lop_t\right], \tag{3.4.4}$$

where $\Lambda_H = \frac{(1-\theta_H)(1-\theta_H\beta)}{\theta_H}$ and $\Lambda_F = \frac{(1-\theta_F)(1-\theta_F\beta)}{\theta_F}$.

3.5 Monetary policy

The monetary authority is modelled using standard forward-looking Taylor rule. This interest rate rule specifies how does the central bank react to expected deviations of CPI inflation and aggregate output from steady state when it decides about policy interest rate. In log-linear terms the Taylor rule can be written down as

$$r_t = (1-\rho)\left(\beta_\pi E_t\pi_{t+1} + \Theta_y E_t y_{t+1}\right) + \rho r_{t-1} + \varepsilon_t^{MP}, \tag{3.5.1}$$

where $\rho \in \langle 0,1\rangle$ is smoothing parameter, $\beta_\pi > 1$ represents the elasticity of policy interest rate with respect to the expected CPI inflation[18] , $\Theta_y \geq 0$ stands for the elasticity of policy interest rate with respect to the expected output gap and $\varepsilon_t^{MP} \sim iid(0,\sigma_{MP}^2)$ is the monetary policy shock.

3.6 Foreign sector

Following Christiano *et al.* (2011), the foreign economy variables are modelled using a VAR(1) model of this form,

$$\begin{pmatrix} y_t^* \\ \pi_t^* \\ r_t^* \end{pmatrix} = \begin{pmatrix} \rho_{y^*y^*} & \rho_{y^*\pi^*} & \rho_{y^*r^*} \\ \rho_{\pi^*y^*} & \rho_{\pi^*\pi^*} & \rho_{\pi^*r^*} \\ \rho_{r^*y^*} & \rho_{r^*\pi^*} & \rho_{r^*r^*} \end{pmatrix} \begin{pmatrix} y_{t-1}^* \\ \pi_{t-1}^* \\ r_{t-1}^* \end{pmatrix} + \begin{pmatrix} 1 & 0 & 0 \\ \sigma_{\pi^*y^*} & 1 & 0 \\ \sigma_{r^*y^*} & \sigma_{r^*\pi^*} & 1 \end{pmatrix} \begin{pmatrix} \varepsilon_t^{y^*} \\ \varepsilon_t^{\pi^*} \\ \varepsilon_t^{r^*} \end{pmatrix}, \tag{3.6.1}$$

where $\varepsilon_t^{y^*} \sim iid(0,\sigma_{y^*}^2)$, $\varepsilon_t^{\pi^*} \sim iid(0,\sigma_{\pi^*}^2)$ and $\varepsilon_t^{r^*} \sim iid(0,\sigma_{r^*}^2)$. Autocorrelation coefficients satisfy $\rho_{y^*y^*}, \rho_{\pi^*\pi^*}, \rho_{r^*r^*} \in \langle 0,1\rangle$. Remaining coefficients are not constrained.

For the purposes of estimation, the VAR structure allows us to identify the exogenous shocks in foreign variables better. Since we assume interdependency of foreign exogenous shocks a shock in foreign output will at the same time influence also foreign CPI inflation and foreign interest rate, and similarly, a shock in foreign CPI inflation will have instant impact on foreign interest rate. Compared to foreign variables modelled as independent AR(1) processes this approach should capture the relations between foreign variables more closely.

[18]We assume that the Taylor principle holds and the central bank adjusts the policy interest rate more than one-for-one with inflation. Violation of this condition can lead even to indeterminacy of equilibrium, see Davig and Leeper (2007) for more details.

3.7 Market clearing and equilibrium

3.7.1 Domestic bond market

Financial intermediaries sell domestic bonds to households and lend obtained funds to entrepreneurs. All the financial intermediaries are assumed to operate at perfectly competitive market, generating no profits. The intermediary borrows the funds from households at cost R_t and receives returns from entrepreneurs of $R_t \left(\frac{N_{t+1}}{Q_t K_{t+1}}\right)^{-\chi} > R_t$. The risk premium $EFP_{t+1} = \left(\frac{N_{t+1}}{Q_t K_{t+1}}\right)^{-\chi}$ is assumed to exactly cover the monitoring costs to fulfill the zero-profit condition. Thus, in equilibrium the intermediaries lend all the funds obtained from households to entrepreneurs,

$$F_t = D_t.$$

3.7.2 Foreign bond market

Households can also buy foreign bonds that yield debt-elastic interest rate $R_t^* \Psi^B(Z_t, A_t^{UIP})$. The higher the amount of foreign bonds kept by the households, the lower the risk-premium $\Psi^B(Z_t, A_t^{UIP})$ and the lower the returns. Since the households can hold negative amounts of foreign bonds as well, this relation works also vice versa. The higher the debt of households, the higher the risk-premium and the higher the costs. Since the risk-premium of foreign bonds is given by net foreign assets position (and exogenous UIP shocks), we need to describe the behaviour of this variable. Net foreign assets position Z_t is defined as a ratio of foreign bonds value and nominal GDP,

$$Z_t = \frac{S_t B_t}{P_{H,t} Y_{H,t}}.$$

The evolution of net foreign assets position can be, therefore, approximated by following log-linear equation[19]

$$z_t = \frac{1}{\beta} z_{t-1} + \gamma y_t^* + \gamma \frac{2\eta - \gamma\eta - 1}{1-\gamma} rer_t + \frac{\gamma - \eta}{1-\gamma} lop_t - \gamma \frac{\overline{C}}{\overline{Y}_H} c_t - \gamma \frac{\overline{INV}}{\overline{Y}_H} inv_t. \tag{3.7.1}$$

3.7.3 Aggregate budget constraint

The production of domestic firms, the gross domestic product, is either consumed and invested in the domestic economy or it is exported to the foreign economy,

$$Y_{H,t} = C_{H,t} + INV_{H,t} + C_{H,t}^*.$$

Using the domestic demand for home goods (3.1.6) and its analogue for investment demand and also the foreign demand for home goods (B.5.2) we get the aggregate resource constraint,

$$Y_{H,t} = \left(\frac{P_{H,t}}{P_t}\right)^{-\eta} \left[(1-\gamma)(C_t + INV_t) + \gamma \left(\frac{1}{RER_t}\right)^{-\eta} Y_t^*\right],$$

which in log-linear terms means

$$y_{H,t} = \frac{\overline{C}}{\overline{Y}_H}(1-\gamma)c_t + \frac{\overline{INV}}{\overline{Y}_H}(1-\gamma)inv_t + \gamma y_t^* + \frac{\eta\gamma(2-\gamma)}{1-\gamma} rer_t - \frac{\eta\gamma}{1-\gamma} lop_t. \tag{3.7.2}$$

[19] The derivation of this result can be found in the appendix B, section B.5.1.

3.8 Log-linearized equations

The model can be summarized by following set of log-linear equations:

- intratemporal optimality condition of households,

$$l_{H,t} = \frac{w_{H,t}}{\Psi} - \frac{c_t - \Upsilon c_{t-1}}{\Psi(1-\Upsilon)}, \tag{3.8.1}$$

- intertemporal optimality condition of households,

$$r_t = \frac{c_{t+1} - \Upsilon c_t}{1-\Upsilon} - \frac{c_t - \Upsilon c_{t-1}}{1-\Upsilon} + E_t \pi_{t+1}, \tag{3.8.2}$$

- uncovered interest parity condition,

$$rer_{t+1} - rer_t = (r_t - E_t \pi_{t+1}) - (r_t^* - E_t \pi_{t+1}^*) + \psi^B z_t + \psi^B a_t^{UIP}, \tag{3.8.3}$$

- equilibrium gross rental rate of capital,

$$r_{G,t} = y_{H,t} + mc_{H,t} - k_t - \left[\frac{\gamma}{1-\gamma}(rer_t - lop_t)\right], \tag{3.8.4}$$

- equilibrium wage of households,

$$w_{H,t} = y_{H,t} + mc_{H,t} - l_{H,t} - \left[\frac{\gamma}{1-\gamma}(rer_t - lop_t)\right], \tag{3.8.5}$$

- equilibrium wage of entrepreneurs,

$$w_{E,t} = y_{H,t} + mc_{H,t} - \left[\frac{\gamma}{1-\gamma}(rer_t - lop_t)\right], \tag{3.8.6}$$

- intermediate goods production function,

$$y_{H,t} = \alpha k_t + (1-\alpha)\Omega l_{H,t} + a_t^Y, \tag{3.8.7}$$

- law of motion for capital,

$$k_{t+1} = \delta inv_t + (1-\delta) k_t, \tag{3.8.8}$$

- equilibrium real price of capital,

$$q_t = \psi^I \delta (inv_t - k_t), \tag{3.8.9}$$

- gross return on capital investment definition,

$$r_{K,t} = \left(1 - \frac{1-\delta}{\overline{R}_K}\right) r_{G,t} + \frac{1-\delta}{\overline{R}_K} q_t - q_{t-1}, \tag{3.8.10}$$

- capital investment optimality condition of entrepreneurs,

$$E_t r_{K,t+1} = r_t - E_t \pi_{t+1} - \chi(n_{t+1} - q_t - k_{t+1}), \tag{3.8.11}$$

- law of motion for entrepreneurial net worth,

$$n_{t+1} = (1-\varsigma)\overline{R}_K \Big[(\Gamma+1)r_{K,t} - \chi\Gamma(q_{t-1}+k_t) - \Gamma(r_{t-1}-\pi_t) + (\chi\Gamma+1)n_t + \\ + a_t^{NW}\Big] + (\Gamma+1)\frac{\overline{W}_E}{\overline{K}} w_{E,t}, \tag{3.8.12}$$

- domestic CPI inflation,

$$\pi_t = \frac{1}{1+\kappa\beta}\left[\beta E_t \pi_{t+1} + \kappa\pi_{t-1} + (1-\gamma)\Lambda_H mc_{H,t} + \gamma\Lambda_F lop_t\right], \tag{3.8.13}$$

- domestic monetary policy rule,

$$r_t = (1-\rho)\left(\beta_\pi E_t \pi_{t+1} + \Theta_y E_t y_{t+1}\right) + \rho r_{t-1} + \varepsilon_t^{MP}, \tag{3.8.14}$$

- law of motion for net foreign assets position,

$$z_t = \frac{1}{\beta} z_{t-1} + \gamma y_t^* + \gamma \frac{2\eta - \gamma\eta - 1}{1-\gamma} rer_t + \frac{\gamma-\eta}{1-\gamma} lop_t - \gamma \frac{\overline{C}}{\overline{Y}_H} c_t - \gamma \frac{\overline{INV}}{\overline{Y}_H} inv_t, \tag{3.8.15}$$

- gross domestic product definition, aggregate budget constraint,

$$y_{H,t} = \frac{\overline{C}}{\overline{Y}_H}(1-\gamma)c_t + \frac{\overline{INV}}{\overline{Y}_H}(1-\gamma)inv_t + \gamma y_t^* + \frac{\eta\gamma(2-\gamma)}{1-\gamma} rer_t - \frac{\eta\gamma}{1-\gamma} lop_t, \tag{3.8.16}$$

- exogenous stochastic process for law of one price gap shock,

$$lop_t = \rho_{LOP} lop_{t-1} + \varepsilon_t^{LOP}, \tag{3.8.17}$$

- exogenous stochastic process for domestic productivity shock,

$$a_t^Y = \rho_Y a_{t-1}^Y + \varepsilon_t^Y, \tag{3.8.18}$$

- exogenous stochastic process for debt-elastic interest rate shock,

$$a_t^{UIP} = \rho_{UIP} a_{t-1}^{UIP} + \varepsilon_t^{UIP}, \tag{3.8.19}$$

- exogenous stochastic process for shock in entrepreneurial net worth,

$$a_t^{NW} = \rho_{NW} a_{t-1}^{NW} + \varepsilon_t^{NW}, \tag{3.8.20}$$

- exogenous VAR(1) block for foreign variables,

$$\begin{pmatrix} y_t^* \\ \pi_t^* \\ r_t^* \end{pmatrix} = \begin{pmatrix} \rho_{y^*y^*} & \rho_{y^*\pi^*} & \rho_{y^*r^*} \\ \rho_{\pi^*y^*} & \rho_{\pi^*\pi^*} & \rho_{\pi^*r^*} \\ \rho_{r^*y^*} & \rho_{r^*\pi^*} & \rho_{r^*r^*} \end{pmatrix} \begin{pmatrix} y_{t-1}^* \\ \pi_{t-1}^* \\ r_{t-1}^* \end{pmatrix} + \begin{pmatrix} 1 & 0 & 0 \\ \sigma_{\pi^*y^*} & 1 & 0 \\ \sigma_{r^*y^*} & \sigma_{r^*\pi^*} & 1 \end{pmatrix} \begin{pmatrix} \varepsilon_{y_t^*} \\ \varepsilon_{\pi_t^*} \\ \varepsilon_{r_t^*} \end{pmatrix}. \tag{3.8.21}$$

3.9 Steady state conditions

Following conditions are assumed to hold in steady state:

- $\overline{P} = \overline{P}_H = \overline{P}_F = \overline{P}^* = 1$,
- $\overline{lop} = 0 \Rightarrow \overline{P}_F = \overline{SP}^*$,
- $\overline{A}^Y = \overline{A}^{UIP} = \overline{A}^{NW} = 1$,
- $\overline{D} = \overline{B} = 0 \Rightarrow \overline{Z} = \frac{\overline{SB}}{\overline{Y}_H \overline{P}_H} = 0$,
- $\overline{R}_G = \alpha \frac{\overline{Y}_H \overline{P}_H^W \overline{P}_H}{\overline{K}\overline{P}_H \overline{P}} \Rightarrow \frac{\overline{Y}_H}{\overline{K}} = \overline{R}_G \frac{\mu}{\alpha}$,
- $\frac{\overline{C}}{\overline{Y}_H} = 1 - \frac{\overline{INV}}{\overline{Y}_H}$,
- $\overline{R}_K = \left(\frac{\overline{N}}{\overline{QK}}\right)^{-\chi} \overline{R} = \left(\frac{\overline{N}}{\overline{K}}\right)^{-\chi} \frac{1}{\beta}$,
- $\overline{R}_K = \frac{\overline{R}_G + (1-\delta)\overline{Q}}{\overline{Q}} \Rightarrow \overline{R}_G = \left(\frac{\overline{N}}{\overline{K}}\right)^{-\chi} \frac{1}{\beta} - (1-\delta)$,
- $\frac{\overline{W}_E}{\overline{K}} = (1-\alpha)(1-\Omega)\frac{\overline{Y}_H}{\overline{K}}$,
- $\overline{\pi} = \overline{\pi}_H = \overline{\pi}_F = \overline{\pi}^* = 0$,
- $\overline{S} = \overline{RER} = 1$,
- $\frac{\overline{P}_H^W}{\overline{P}_H} = \overline{MC}_H = \frac{1}{\mu} = \frac{\varepsilon - 1}{\varepsilon}$,
- $\overline{R} = \frac{1}{\beta}$,
- $\overline{INV} = \delta \overline{K}$,
- $\frac{\overline{INV}}{\overline{Y}_H} = \delta \frac{\overline{K}}{\overline{Y}_H}$,

3.10 Model with monetary policy regime switch

In the case of the Slovak economy, the structure described above is relevant only to the period prior to its accession to the euro area, in other words until the end of 2008.[20] An additional observable time series sw_t is included in the model to indicate the deterministic regime switch from independent monetary policy ($sw_t = 0$) with separate currency to monetary union with common monetary policy and common currency after the beginning of 2009 ($sw_t = 1$). In modelling terms, the monetary policy regime switch is carried out by an exogenous shock innovation, and thus, it is modelled as an unexpected change, similarly to Senaj *et al.* (2010).

Alternatively, the regime switch could be modelled as anticipated change, which would probably make the model assumptions more realistic. Kulish and Pagan (2014) developed a solution for the linear models where agents form expectations about the changing structure of the model economy. In our case, this approach is not directly applicable and would have to be extended, because we work with a nonlinear DSGE model. Also, this approach brings about non-trivial announcement effects and requires a pinpointing of the particular moment when the agents found out about the forthcoming structural change.[21]

[20] The regime switch is executed in 2009Q1. Another possibility would be to place the regime switch at some point during the ERM II period; however, the exact point is unclear. Another possibility would be to assume gradual phasing-in during the ERM II with an incremental transition instead of the 0/1 switch. However, due to the strong appreciation of the Slovak koruna in ERM II, which necessitated multiple central parity adjustments and different settings of the nominal interest rate in Slovakia than in the euro area, we chose the approach described in the main text.

[21] This moment should most likely be the July 8, 2008, when the European Council approved the accession of Slovakia to the euro area and it became certain that the euro would be introduced in Slovakia on January 1, 2009. However, the expectations about the euro adoption in Slovakia were probably forming even before this date, maybe as early as since November 25, 2005, when the Slovak authorities decided that the Slovak koruna should be included in the ERM II exchange rate mechanism. Since all new member states that joined the European Union on May 1, 2004, are required to adopt the common European currency in the future, it could be argued that expectations about the future euro adoption and monetary

The regime switch changes two model equations, the Taylor rule and the uncovered interest parity (UIP) condition. By changing the observed binary variable sw_t from 0 to 1 we can switch between the alternative specifications of these two crucial model equations. In log-linear terms, the equation that is affected by the regime switch can, in general, be written down as

$$(1 - sw_t) \cdot lhs_1 + sw_t \cdot lhs_2 = (1 - sw_t) \cdot rhs_1 + sw_t \cdot rhs_2. \tag{3.10.1}$$

The setting of the policy interest rate is decided outside the member economies of the monetary union. Due to the size of the Slovak economy and its share of the total euro area GDP, we can consider the nominal interest rate to be given exogenously. Therefore, the Taylor rule equation (3.5.1) is replaced by

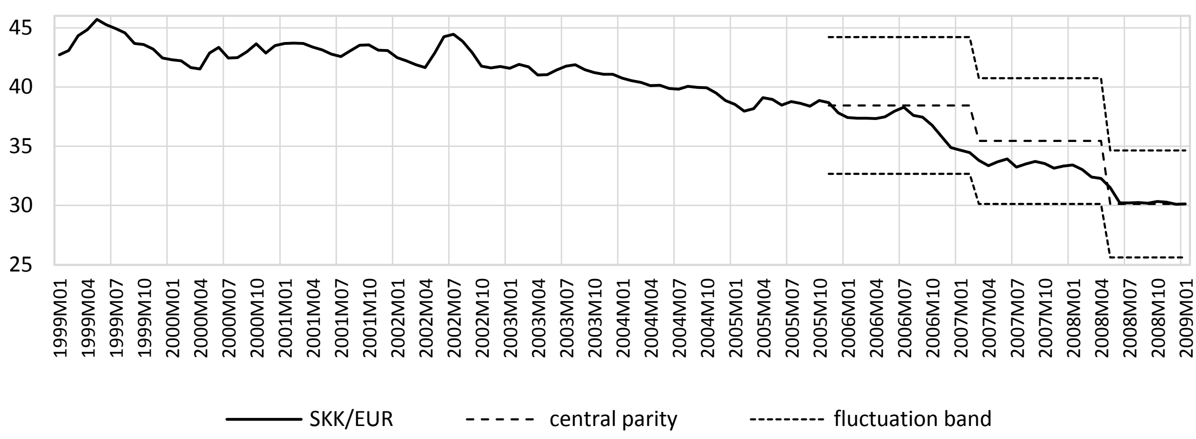
$$i_t = i_t^*. \tag{3.10.2}$$

The original forward-looking UIP condition (3.2.7) describes the development of the real exchange rate rer_t in terms of the real interest rate differential and the risk premium, which is a function of net foreign assets z_t and contains an exogenous AR(1) component, the UIP shock. As in monetary union the nominal interest rates are equal by definition, the UIP equation changes to

$$rer_t - rer_{t-1} = \pi_t^* - \pi_t + \psi_B \cdot z_t + a_t^{UIP}. \tag{3.10.3}$$

The development of the real exchange rate in the monetary union is mainly driven by the inflation differential. In order to resolve the transition from a situation when the central parity of an appreciating currency in a converging economy is set below the steady state (the domestic currency is too strong), we keep the risk premium component present in the UIP condition.[22]

Figure 3.1: The nominal exchange rate of Slovak koruna



Source: Author, Data: ECB.

policy regime switch were forming even back then. Thus, it is not a trivial problem to exactly pinpoint the moment when the expectations about the forthcoming structural change start to form and some simplification is always necessary.

[22]It would also be possible to include the risk premium in the monetary policy rule instead. This would correspond to a situation with the common currency already in place and monetary policy would switch to an exchange rate targetting regime. This setting would correlate with the observed reality, where the availability of funds (foreign bonds) remains rather heterogenous across the euro area countries. However, this approach does not deal with the adjustment of the real exchange rate from below the steady state after the adoption of the euro currency.

The exchange rate of the Slovak koruna together with its central parity and ±15 per cent fluctuation band is depicted in Figure 3.1. The central parity of the Slovak koruna was set to 38.4550 SKK/EUR in November 2005, when Slovakia entered the ERM II mechanism. In March 2007, it was adjusted to 35.4424 SKK/EUR and further to 30.1260 SKK/EUR in May 2008. The problem was that the strong appreciation of the Slovak koruna in this period was not only a manifestation of economic convergence, but also driven by the business cycle. In a floating exchange rate regime the Slovak koruna would probably have depreciated during late 2008 and early 2009, as did the Czech currency (see Figure 1.2). In retrospect, the second adjustment of the central parity to the value of the former lower bound in May 2008 probably led to a situation where the central parity was set below the steady state.

3.11 Time-varying parameters

The time-varying parameters are defined as unobserved endogenous variables with following law of motion

$$\theta_t = (1 - \alpha_t^{\theta}) \cdot \theta_{t-1} + \alpha_t^{\theta} \cdot \overline{\theta} + \nu_t^{\theta} \tag{3.11.1}$$

where θ_t is a general time-varying parameter, $\overline{\theta}$ is initial value of this parameter, α_t^{θ} is a time-varying adhesion parameter common for all the remaining time-varying parameters and $\nu_t^{\theta} \sim N(0, \sigma_{\nu}^{\theta})$ is exogenous innovation in the value of parameter θ_t. Setting of the adhesion parameter α_t^{θ} influences the tendency of the time-varying parameter θ_t to return to its initial value $\overline{\theta}$. With $\alpha_t^{\theta} = 0$, the time-varying parameter would be defined as random walk, while with $\alpha_t^{\theta} = 1$, the parameter would be white noise centred around the initial value $\overline{\theta}$. The adhesion parameter α_t^{θ} is common for all the remaining time-varying parameters and is itself considered time-varying with adhesion set to 0.01 and initial value α_0^{θ} calibrated to 0.25. The adhesion parameter is therefore virtually free to drift away from its initial value. Sensitivity of the results to the calibration of the initial value of the adhesion parameter is assessed in section 6.1.

In the baseline specification, all the model parameters are considered time-varying with the exception of shock autoregression parameters, standard deviations, SVAR(1) block parameters and Taylor rule smoothing parameter. Sensitivity of the results to the choice of time-varying and time-invariant parameters is evaluated in section 6.2.

Chapter 4

Methodology

In this chapter, theoretical foundations of applied estimation methods are described. The solution of dynamic models under rational expectations is briefly discussed in the first part of this chapter. In the second part, Bayesian methods of system parameters identification are described, with most attention given to the Random Walk Metropolis-Hasting algorithm. Substantial parts of this chapter were already presented in much the same form in Tvrz (2011) and with minor modifications they are integrated into this thesis.

4.1 Dynamic models with rational expectations

As shown in Blanchard and Kahn (1980), a wide spectrum of forward-looking dynamic models with rational expectations can be written in recursive form,

$$\begin{pmatrix} X_{t+1} \\ {}_tP_{t+1} \end{pmatrix} = A \begin{pmatrix} X_t \\ P_t \end{pmatrix} + \gamma Z_t,\ X_{t=0} = X_0, \tag{4.1.1}$$

$$ {}_tP_{t+1} = E(P_{t+1}|\Omega_t), \tag{4.1.2}$$

$\forall t \exists \widetilde{Z}_t \in \mathbb{R}^k$, $\rho_t \in \mathbb{R}$ such that

$$-(1+i)^{\rho_t}\widetilde{Z}_t \leq E(Z_{t+1}|\Omega_t) \leq (1+i)^{\rho_t}\widetilde{Z}_t,\ \forall i \geq 0. \tag{4.1.3}$$

Equation (4.1.1) represents the structure of the model. We distinguish predetermined and non-predetermined variables (forward-looking). X_{t+1} is an $(n \times 1)$ vector of predetermined variables at time $t+1$, P_{t+1} is an $(m \times 1)$ vector of non-predetermined variables at time $t+1$. Left subscript in ${}_tP_{t+1}$ indicates agents' expectations of value P_{t+1} at time t. Z is a $(k \times 1)$ vector of exogenous variables. A is constant matrix $(n+m) \times (n+m)$ and γ is constant matrix $(n+m) \times k$.

The values of predetermined variables at time $t+1$ are functions of past, and hence, known values of variables at time t. Ω_t represents the information set at time t containing all the available information at that time. Predetermined variables do not depend on expectations of future values and are given by Ω_t. This means that equation ${}_tX_{t+1} = X_{t+1}$ always holds. Non-predetermined variables can be also functions of variables from Ω_{t+1}. This means that ${}_tP_{t+1} = P_{t+1}$ holds only if the realizations of Ω_{t+1} equal to their expectations at time t.

Equation (4.1.2) shows the rationality of expectations in the model. Ω_t consists of past and current values of X, P and Z. It follows that $\Omega_t \supseteq \Omega_{t-1}$. The rationality is implied by the fact that the agents use all the available information at time t (Ω_t) when forming their expectations. The equation (4.1.3) excludes exponential behaviour of exogenous variables Z.

4.1.1 State-space representation

Analytical solution of the model can be obtained using Jordan canonical form of matrix A, $A = C^{-1}JC$, where J is diagonal matrix of eigenvalues. The existence and uniqueness of the solution then depends on the number of eigenvalues lying outside the unit circle, $\widetilde{m}$, and the number of non-predetermined variables, m. The system has unique solution if $\widetilde{m} = m$, it has infinity of solutions if $\widetilde{m} < m$ and it has no solution when $\widetilde{m} > m$. Note that this method cannot be used for models with past expectations of current and future variables. In general, these models cannot be written in required form. In that case we can use generalized Schur method (QZ decomposition) as described in Klein (2000).

After finding the decomposition of matrix A the model can be then rewritten in a state-space representation,

$$\begin{aligned} X_{t+1} &= A(\theta)X_t + B(\theta)V_{t+1}, \\ Y_t &= C(\theta)X_t + D(\theta)W_t, \end{aligned} \tag{4.1.4}$$

where X_t is a vector of endogenous variables, Y is a vector of observed values (measurements), V_t is a vector of exogenous variables (shocks), satisfying $V_t \sim N(0, \Sigma_V)$, W_t is a vector of measurement errors, satisfying $W_t \sim N(0, \Sigma_W)$, and A, B, C, D are matrix functions of vector of unknown parameters θ.

4.1.2 Kalman filter

As shown in Mancini Griffoli (2010) we can write down the solution to the linearized-model (4.1.4) as following system of equations,

$$Y_t = M\overline{X}(\theta) + Mx_t + N(\theta)Q_t + W_t, \tag{4.1.5}$$

$$x_t = g_x(\theta)x_{t-1} + g_V(\theta)V_t, \tag{4.1.6}$$

$$E(W_tW_t') = W(\theta), \tag{4.1.7}$$

$$E(V_tV_t') = V(\theta). \tag{4.1.8}$$

In equation (4.1.5), the observed variables Y_t are described as functions of steady state values $\overline{X}$, deviations from steady state x_t, trend term $N(\theta)Q_t$ and measurement error W_t. Matrix M is a constant matrix, matrix N is a function of the vector of structural parameters θ. The equation (4.1.6) represents the decision rule of endogenous variables. Equations (4.1.7) and (4.1.8) represent covariance matrices of measurement errors and exogenous variables respectively.

Equations (4.1.5) and (4.1.6) form a system of measurement and transition, i.e. state-space equations. Therefore we can use Kalman filter to estimate marginal likelihood. For initial values Y_1 and P_1 the algorithm recursively calculates

$$V_t = Y_t - \overline{Y} - Mx_t - NQ_t, \tag{4.1.9}$$

$$F_t = MP_tM' + V, \tag{4.1.10}$$

$$K_t = g_xP_tg_x'F_t^{-1}, \tag{4.1.11}$$

$$x_{t+1} = g_xx_t + K_tV_t, \tag{4.1.12}$$

$$P_{t+1} = g_xP_t(g_x - K_tM)' + g_WQg_W', \tag{4.1.13}$$

for $t = 1, \ldots, T$. To find the posterior distribution of model parameters, we can derive the log-likelihood $\ln \mathcal{L}(\Theta|Y_T)$ as

$$\ln \mathcal{L}(\Theta|Y_T) = -\frac{T}{2}\ln(2\pi) - \frac{1}{2}\sum_{t=1}^{T}\ln|F_t| - \frac{1}{2}V_t'F_t^{-1}V_t, \tag{4.1.14}$$

where Θ contains $\theta, V(\theta)$ and $Q(\theta)$ and Y_T stands for the set of observable variables Y_t.

By combining log-likelihood and prior information we obtain log posterior kernel. The logarithm of posterior probability density of structural parameters is hence proportional to

$$\ln \mathcal{K}(\theta|Y_T) = \ln \mathcal{L}(\theta|Y_T) + \ln p(\theta). \tag{4.1.15}$$

4.2 Bayesian estimation

To find the estimated values of vector of parameters θ, we can use Bayesian methods. We are interested in conditional probability distribution of θ for given observed data y, i.e. posterior density $p(\theta|y)$. From Bayes theorem we get

$$p(\theta|y) = \frac{p(y|\theta)p(\theta)}{p(y)}. \tag{4.2.1}$$

Posterior density is given by likelihood function $p(y|\theta)$, prior density $p(\theta)$ and data density $p(y)$. Since $p(y)$ is constant for given measurements, the posterior density is proportional to the product of likelihood function and prior density,

$$p(\theta|y) \propto p(y|\theta)p(\theta). \tag{4.2.2}$$

We can specify the prior density based on our experience and expectations. For likelihood function calculation we can use Kalman filter. Vector θ estimate based on observed data is then given by

$$E(\theta) = \int_\theta \theta \cdot p(\theta|y)\, \mathrm{d}\theta. \tag{4.2.3}$$

4.2.1 Random walk Metropolis-Hastings

Since we do not know the explicit form of $p(\theta|y)$ distribution, we cannot compute the estimate $E(\theta)$ directly. We can, however, employ sampling-like methods. In this thesis we used Random Walk Metropolis-Hastings algorithm. This method is well described in Mancini Griffoli (2010) and Koop (2003).

This algorithm generates a sequence θ^i, $i = 1, \ldots, N$ from distribution $p(\theta|y)$. The candidate draws are generated by following formula,

$$\theta^+ = \theta^{n-1} + z, \tag{4.2.4}$$

where z is called increment random variable. The equation (4.2.4) clearly shows that the candidates are generated by random walk algorithm.

We define auxiliary density function $q(\theta^+, \theta^{n-1})$. This density function is called candidate generating density and it is conditional density of draw θ^+ depending on preceding realisation θ^{n-1}. This density function determines the characteristics of z as well, $z \sim N(0, \Sigma)$. Usually we choose multivariate normal distribution of following form,

$$q(\theta^+, \theta^{n-1}) = f_N(\theta|\theta^{n-1}, \Sigma). \tag{4.2.5}$$

The acceptance probability $\alpha(\theta^+, \theta^{n-1})$ is the probability of accepting newly generated draw into the sequence θ^i. By definition, the Metropolis-Hastings algorithm tends to stay in high posterior probability region. The acceptance probability has to be constructed so as to allow the algorithm to visit the regions with lower posterior probabilities as well. Correctly defined acceptance probability is given by

$$\alpha(x,y) = \min\left[1, \frac{g(y)q(x,y)}{g(x)q(x,y)}\right], \tag{4.2.6}$$

where $g(x) = p(y|\theta)p(\theta)$ and $q(x,y) = \phi(x-y)$ is the probability density of the multidimensional normal distribution with zero mean and diagonal covariance matrix. Since the auxiliary density is symmetric around zero, we can simplify the equation (4.2.6) to

$$\alpha(x,y) = \min\left[1, \frac{g(y)}{g(x)}\right]. \tag{4.2.7}$$

For n-th member of the θ^i sequence, we draw a candidate θ^+ from $q(\theta^+, \theta^{n-1})$ and assign $\theta^n = \theta^+$ with the probability $\alpha(\theta^+, \theta^{n-1})$ or $\theta^n = \theta^{n-1}$ otherwise.

The value of initial guess θ^0 and the covariance matrix Σ that defines the candidate generating density can be set according to the results of maximal likelihood method. Using the numerical methods of multivariate optimization, we find the θ^0 as the combination of parameter values that maximizes the likelihood function, i.e. the posterior mode. To obtain the covariance matrix Σ, we compute

$$\Sigma := var(\theta_{ML}) = I(\theta)^{-1} = \left[-E\left(\frac{\partial^2 \ln p(y|\theta)}{\partial\theta\partial\theta'}\right)\right]^{-1}, \tag{4.2.8}$$

where θ_{ML} is maximum likelihood estimate of θ and $I(\theta)$ is information matrix. According to Koop (2003) and asymptotic theory, the larger the sample size, the better does the inverse information matrix describe the posterior density. However, this method is not always able to find the posterior mode and obtained matrix Σ can have non-positive eigenvalues. In that case the matrix is not positively definite and it cannot be used as covariance matrix.

To remove the effect of chosen initial value θ^0 of the algorithm, we discard first part of the sequence θ^i. Let $N_2 = N - N_1$ be the number of draws in θ^i we have left. Because all the remaining draws have the same weight and importance, we obtain the estimates of structural parameters by simple averaging of the remaining values in sequence θ^i,

$$E(\theta) = \frac{1}{N_2}\sum_{i=N_1+1}^{N} \theta^i. \tag{4.2.9}$$

We can summarize the Metropolis-Hastings algorithm in following sequence of steps,

0. Choose initial value, θ^0.
1. Generate a new candidate θ^+ from candidate density $q(\theta^+, \theta^{n-1})$.
2. Compute acceptance probability $\alpha(\theta^+, \theta^{n-1})$.
3. Assign $\theta^n = \theta^+$ with probability α or $\theta^n = \theta^{n-1}$ with probability $1-\alpha$.
4. Repeat the steps 1 through 3 N times.
5. Discard first N_1 members of sequence θ^i.
6. Compute the average of remaining draws $\theta^{N_1+1}, \dots, \theta^N$.

Note that we can use this method to find the estimates of any function of structural parameters, $h(\theta)$ as well. Instead of calculating the average of draws θ^i we would compute the average of the function values $h(\theta^i)$.

In this thesis, two Random Walk Metropolis-Hastings chains of 1 000 000 draws each were generated for every estimated model. First 50 % draws in both chains were discarded before computing the posterior estimates. Scaling parameter of the candidate density covariance matrix Σ was chosen so as to achieve acceptance rate between 0.25 and 0.3.

4.2.2 Recursive estimation

Recursive estimation is a method that enables us to see changing structure of the model as the time flows. Using the random walk Metropolis-Hastings algorithm we estimated a sequence of models with varying historical data input. Let T be the total number of observations. We choose number of observations $t < T$ and estimate models with first t, $t+1,\ldots,T$ observations of historical data. We can then use the output of this recursive estimation to see the effects of new information in added observations on estimates of structural parameters and other model characteristics. Results of recursive estimation are used in section 6.3 to assess robustness of the results of nonlinear particle filter estimates of time-varying parameters.

In this thesis we used recursive estimation with $t = 21$. This means that all the estimates of this recursive algorithm are based on at least 21 quarters of historical data. In each estimation we used two Metropolis-Hastings runs with 100 000 samples each. First 50 % draws were discarded.

4.2.3 Shock decomposition

Shock decomposition is a method that calculates the effects of smoothed exogenous shock innovations on development of endogenous variables. The variance of endogenous variables can be decomposed into distinct contributions of exogenous shocks. This method is also called historical decomposition because it allows us to see what effects did different shocks have in different moments of time. By using bar plot to present the output of this method we can easily compare the relative importance of individual shocks.

4.3 Model with time-varying parameters

By introduction of the time-varying parameters into the DSGE model, the DSGE model becomes highly nonlinear. The state-space representation of the DSGE model takes a general form of

$$X_{t+1} = h(X_t, V_t), \tag{4.3.1}$$
$$Y_t = g(X_t, W_t), \tag{4.3.2}$$

where $f(\cdot)$ and $g(\cdot)$ are nonlinear functions. To overcome the computational problems related to nonlinearity, we can take first order approximation of the transition equation around the steady state $\overline{X}$,

$$X_{t+1} = \overline{X} + A \cdot \widehat{X}_t + B \cdot V_t, \tag{4.3.3}$$

where $\widehat{X}_t = X_t - \overline{X}$. This way we would return to a linear model but at a cost of relatively gross simplification of the original nonlinear model. According to Billing (2013), a first-order approximation introduces certainty equivalence into the solution which may be inappropriate in case of welfare analysis or when studying the effects of risk. First order approximation also eliminates any potential asymmetries in the model and ignores the effects of risk. These two problems can be solved by a second-order approximation, that introduces a constant correction for the effects of risk. Taking a third-order approximation would introduces a time varying risk term and an additional correction for the effects of skewed shocks.

In this thesis, we chose a second order approximation to preserve the salient features of the nonlinear model. The transition equation then becomes

$$X_{t+1} = \overline{X} + A \cdot \widehat{X}_t + B \cdot V_t + \frac{1}{2} \cdot C \cdot (\widehat{X}_t \otimes \widehat{X}_t) + D \cdot (\widehat{X}_t \otimes u_t) + \frac{1}{2} \cdot E \cdot (u_t \otimes u_t) + \frac{1}{2} \cdot \Delta^2, \quad (4.3.4)$$

where $\otimes$ denotes a Kronecker product and Δ^2 is the shift effect of the variance of future shocks.

4.3.1 Nonlinear particle filter

Nonlinear particle filter (NPF) is used to identify the unobserved states of the nonlinear DSGE model, including the time-varying parameters, in this thesis. In this section, we briefly describe the main principles of this nonlinear particle filter.

Unlike basic Kalman filter that is optimal only for linear systems with Gaussian noise, the nonlinear particle filter is a more sophisticated tool that can be used even for non-linear state-space systems with non-Gaussian noise. In this section, we provide only the basic principles of the algorithm. A detailed description can be found for example in Van Der Merwe *et al.* (2000) or Yano (2010). In a condensed form, the NPF algorithm can be described as follows:

1. Initialization: $t = 0$, set the prior mean $\overline{x}_0$ and covariance matrix P_0 for the state vector x_t.

2. Generating particles: Draw a total of N particles $x_t^{(i)}$, $i = 1, \ldots, N$ from distribution $p(x_t)$ with mean $\overline{x}_t$ and covariance matrix P_t.

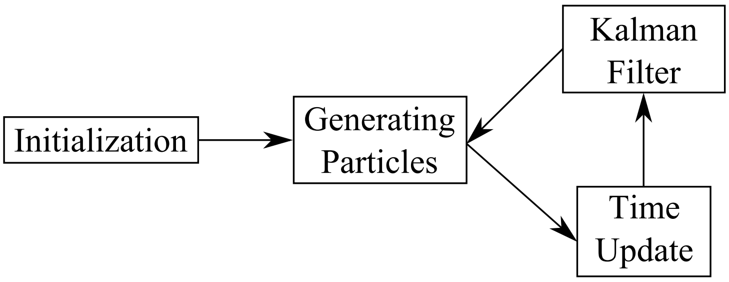
3. Time Update: $t = t + 1$, for each particle ($i = 1, \ldots, N$) propagate the particle into future with the use of nonlinear transition and measurement equation and calculate means $\overline{x}_{t|t-1}$, $\overline{y}_{t|t-1}$ and covariance matrices $P_{t|t-1}$, $P_{y,y}$ and $P_{x,y}$.

4. Kalman filter: Calculate Kalman gain $K_t = P_{x,y} \left(P_{y,y}\right)^{-1}$, $\overline{x}_t = \overline{x}_{t|t-1} + K_t(y_t - \overline{y}_{t|t-1})$ and $P_t = P_{t|t-1} - K_t P_{y,y} \left(K_t\right)^T$

5. Continue by step 2 until $t = t_{max}$.

A diagram of the NPF algorithm is presented in Figure 4.1.

Figure 4.1: Nonlinear particle filter



Source: Author.

In our application we performed 20 runs of the NPF with 30.000 particles each for the second order approximation of the nonlinear DSGE model.[1] Before the application of the NPF algorithm we estimated the model with constant parameters using the random walk Metropolis-Hastings algorithm. The posterior means of the model parameters were used as initial values of the time-varying parameters ($\overline{\theta}$). The standard deviations of time-varying parameters innovations (σ_ν^θ) were set equal to the 10 % of the posterior means of the structural parameters.[2]

[1]The setting of the particle simulation is chosen as a compromise between accuracy and the time demands of the calculation. By experimenting with the setting of the particle filter algorithm we found that the results do not change significantly when the number of runs or the number of particles is increased.

[2]This choice is motivated by the big differences in posterior standard deviations of estimated constant parameters (relative to the posterior means). Posterior standard deviations would be the natural alternative; however, they capture uncertainty associated with the posterior estimate that need not have any relation to the stability of the posterior estimate in time. The parameter in question could be time-invariant and yet hard to estimate, which would yield high posterior standard deviation. Therefore, we decided to calibrate the standard deviations of the time-varying parameters in a uniform way and let the filtration decide which parameters are time-varying.

Chapter 5

Empirical analysis

In this chapter, empirical results of the estimation are presented. First section of this chapter decribes the observables dataset used for estimation. Results of estimation of the models with time-invariant parameters are presented and discussed next. Last part of the chapter presents and compares the results of the estimation of the nonlinear model specification with time-varying parameters. Empirical results for the four Visegrád economies are supplemented by the results of the model estimated on the data of the euro area economy. This is meant as a benchmark that can show the general trends in the developed European economies.

All the computations were carried out in Matlab (version 7.10, release R2010a). The Dynare toolbox[1] (version 4.4.3), developed by Adjemian *et al.* (2011), was used for the Bayesian estimation of the model.

5.1 Data

Quarterly time series of eight observables were used for the purposes of estimation. These ESA 2010 consistent time series cover the period between the first quarter of 1999 and the fourth quarter of 2014 and contain 64 observations. Graphs of the observed time series are included in the Appendix C, section C.1.

Seasonally adjusted time series of real gross domestic product (GDP), the harmonised consumer price index (CPI), the 3-month policy interest rate (interbank offered rate) and real investment are used for the domestic economy. In the case of the Visegrád economies, the foreign sector is represented by the 17 Euro area countries, while in the ase of the euro area economy itself, the foreign sector is represented by the U.S. economy. The foreign sector is captured by the seasonally adjusted time series of real GDP, CPI and 3-month policy interest rate. Time series of CZK/EUR, SKK/EUR,[2] PLN/EUR, HUF/EUR and EUR/USD real exchange rates are also used for the purposes of estimation. The time series were obtained from the databases of Eurostat, Czech National Bank, National Bank of Slovakia, Polish National Bank, Hungarian National Bank, European Central Bank and Federal Reserve Bank of St. Louis.

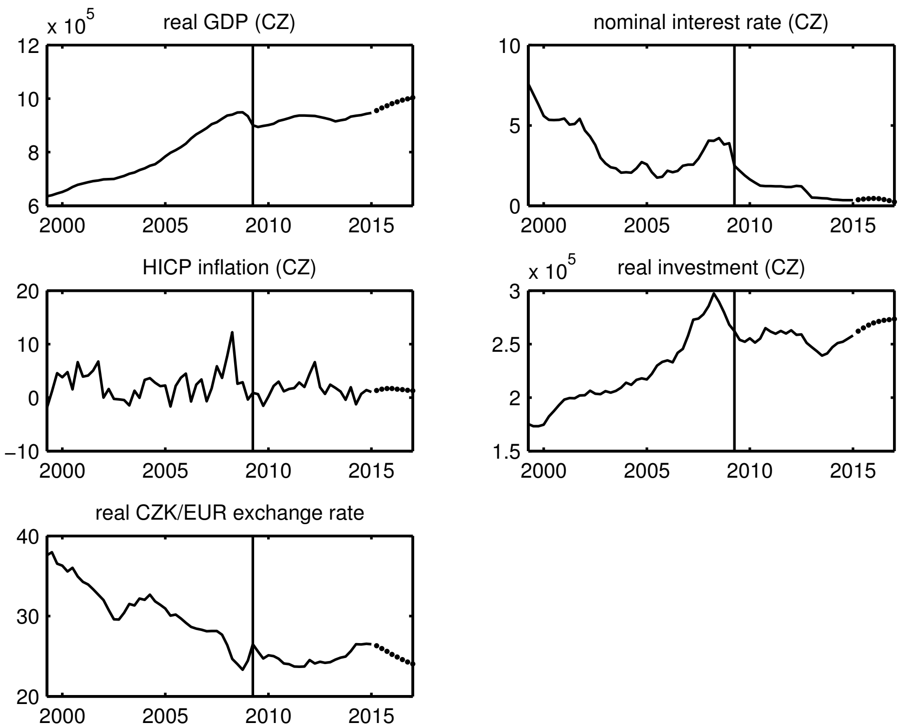
The original time series were transformed prior to estimation so as to express logarithmic deviations from their respective steady states. The logarithmic deviations of the observables from their trends were calculated with the use of Hodrick-Prescott (HP)

[1] `www.dynare.org`

[2] The values of the real exchange rate of the Slovak economy after its accession to the euro area were obtained in accordance with the model definition of the real exchange rate by considering the development of the inflation differential.

filter.[3] In order to mitigate the end-of-sample bias of the HP-filter, the level data were extended by a VAR forecast[4] before the calculation of the logarithmic deviations.

Figure 5.1: CZ domestic block, VAR forecast



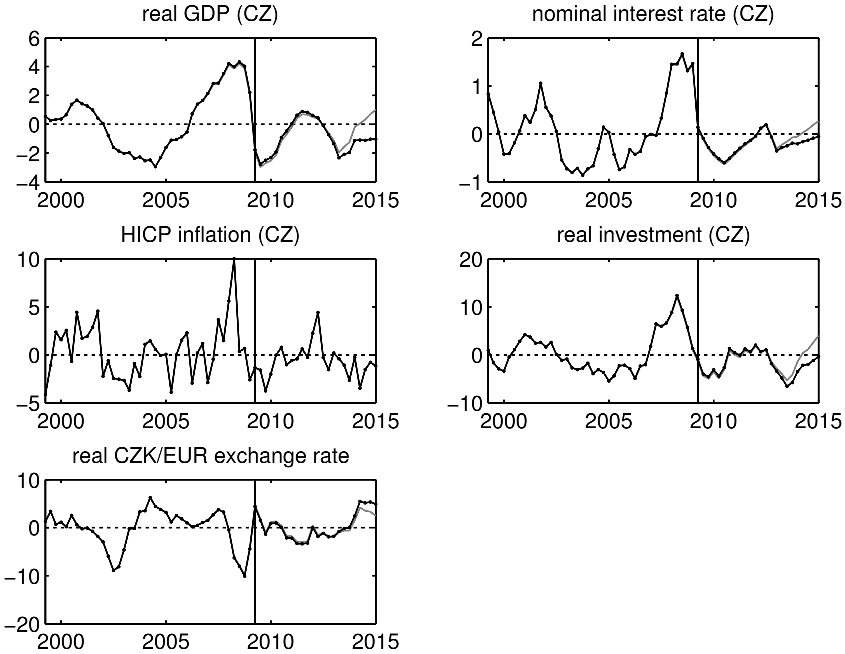
Source: Author, Data: Eurostat, ECB, CNB.
Note: Solid line - observed data, dotted line - conditional VAR forecast, vertical line - 2009Q1.

Figure 5.1 contains the VAR forecast of the domestic block of variables for the Czech economy conditional on the development in the euro area. The forecasts seem to be quite reasonable. The effects of the extension on the end-of-sample bias for the domestic observables of the Czech economy model are depicted in Figure 5.2. The calculation of the HICP inflation gap was practically unaffected by the extension. However, the gaps of remaining domestic observables changed significantly. With the VAR extension, the real output gap remains distinctively negative. Gap in real investment was also reduced and so was the gap of nominal interest rate. On the other hand, the gap of real exchange rate increased. In economic terms, the gaps calculated with the use of VAR forecast suggest that the economy was still operating below its steady state, the real investment was just about to return to steady-state, monetary policy was still kept quite loose and the real exchange rate was still relatively weak. By contrast, the gaps calculated without the VAR extension would suggest relatively unrealistic overheating of the Czech economy with tightening monetary policy and appreciating real exchange rate.

[3]The parameter of the HP filter λ was set to 1600, a value commonly used for quarterly data.

[4]A VAR(3) model was considered for the foreign economy, while a VAR(1) model with three exogenous foreign variables was considered for the domestic economy. The forecast for the next eight quarters was calculated. Due to a structural break (adoption of the euro currency) in the Slovak economy, the time series of nominal interest rate and real exchange rate could not be included in the domestic VAR(1) model for Slovakia.

Figure 5.2: Example of end-of-sample bias correction using VAR forecast, CZ



Source: Author, Data: Eurostat, ECB, CNB.
Note: Per cent deviations from steady state are depicted, black line - data extended with VAR forecast, gray line - observed data only, vertical line - 2009Q1.

5.2 Parameters estimation

In this section, choice of values for the calibrated parameters of the small open economy DSGE models of the four Visegrád economies and the euro area is explained first. Next, prior and posterior distributions of the estimated parameters are reported and compared. Note that the values of calibrated parameters as well as the prior densities of estimated parameters are the same for all the economies in order to identify structural differences in the data.

5.2.1 Calibration

We decided to calibrate several deep structural parameters because they are generally difficult to estimate. These parameters were assigned values commonly reported in the literature and presented in Table 5.1. The value of discount factor β of 0.995 implies real interest rate of approximately 2 % p.a., similar values are reported by Christensen and Dib (2008) or Christiano, Trabandt and Walentin (2011). Capital share in production α corresponds to the national income share of capital of 0.35. Values around one third are usually used in the literature, see Adolfson, Laséen and Villani (2007) or Christiano, Trabandt and Walentin (2011). Capital depreciation rate δ of 2.5 % per quarter is also standard and follows Christensen and Dib (2008). Households' share of labour supply ω is calibrated according to Shaari (2008) to 99 % which leaves the remaining 1 % of the labour supply to be provided by the entrepreneurs. Calibration of steady-state markup parameter μ follows Shaari (2008) as well.

Table 5.1: Calibrated parameters

Parameter		Value
β	discount factor	0.995
α	capital share in production	0.350
δ	capital depreciation rate	0.025
μ	steady-state domestic mark-up	1.200
Ω	households' share in labour supply	0.990

Source: Author, Data: Sources cited in text.

5.2.2 Priors and posteriors

The prior densities of the estimated parameters are presented in Table 5.2. These are the same for all the economies in order to identify structural differences as captured by the observed data. A comparison of the posterior means of all the examined economies is also included in Table 5.2. Posterior means expressed relative to the posterior mean of the Czech economy model are presented in Table 5.3. Detailed results of the estimation for individual models can be found in the tables in Appendix D. Graphs of prior and posterior densities are included in the Appendix C, section C.2, while the graphs of multivariate Brooks and Gelman (1998) convergence diagnostics (as implemented in Dynare toolbox) are included in section C.3.

Prior distributions of model parameters are chosen in a following way. Parameters that take values from $\langle 0, 1\rangle$ are assigned priors with beta distribution. Specifically, for the autocorrelation coefficients of exogenous AR(1) shock processes we choose relatively uninformative beta distribution priors with the mean of 0.5 and standard deviation of 0.2. Structural parameters that are assumed to take values from $\langle 0, \infty)$ are assigned priors with gamma distribution. The steady-state ratio of capital stock and entrepreneurial net worth Γ and the inflation weight in the Taylor rule β_π both have to be larger than one. $\Gamma \leq 1$ would mean that the entrepreneurs are fully self-financing. The entrepreneurs would not need to borrow the external funds, and therefore, their optimality condition would be different than what is assumed in the model. In particular, the external finance premium would become negative in the steady state and the entrepreneurs would then operate with financing costs lower than the policy interest rate, which is rather unrealistic. Similarly, the parameter β_π has to be larger than one so as to fulfill the Taylor principle and to avoid indeterminacy problems. Therefore, parameters Γ and β_π are assigned priors with shifted gamma distribution.[5] The diagonal elements of foreign VAR(1) block $\rho_{y^*y^*}, \rho_{\pi^*\pi^*}$ and $\rho_{r^*r^*}$ are assigned β distribution because they are expected to capture the autocorrelation of foreign observables, and thus, to take values from $\langle 0, 1\rangle$. For the rest of VAR(1) parameters we do not have strong prior belief about their respective values. These parameters are assigned normal distribution priors with zero mean and standard deviation of 0.5. Standard deviations of exogenous shock innovations are expected to be positive and close to zero, therefore, they are assigned priors with inverse-gamma distribution and infinite standard deviation.

While the multivariate convergence diagnostics do not indicate any problems, the graphs of prior and posterior densities show a lack of information about the parameter of consumption habit Υ in the data. The bimodal posterior densities of several parameters in the model of Hungarian economy hint at possible structural changes.

[5] In Dynare, this is achieved by estimating $\Gamma^+ = \Gamma - 1$ and $\beta_\pi^+ = \beta_\pi - 1$ instead of the original parameters. Of course, model equations have to be appropriately adjusted, i.e. β_π has to be replaced by $\beta_\pi^+ + 1$ and Γ has to be replaced by $\Gamma^+ + 1$.

Table 5.2: Posterior means comparison

Parameter		Distrib.	Prior Mean	Prior Std	Posterior mean CZ	SK	PL	HU	EA
Υ	habit persistence	B	0.60	0.05	0.59	0.57	0.58	0.59	0.66
Ψ	inverse elasticity of labour supply	G	2.00	0.50	1.24	1.35	1.31	1.35	1.18
ψ^B	elasticity of debt-elastic risk premium	G	0.05	0.02	0.02	0.05	0.04	0.05	0.02
η	home and foreign goods elasticity of substitution	G	0.65	0.10	0.60	0.74	0.58	0.59	0.46
κ	price indexation	B	0.50	0.10	0.27	0.23	0.36	0.37	0.21
γ	preference bias to foreign goods	B	0.40	0.10	0.29	0.35	0.21	0.24	0.21
θ_H	home goods Calvo parameter	B	0.70	0.10	0.81	0.74	0.78	0.69	0.81
θ_F	foreign goods Calvo parameter	B	0.70	0.10	0.79	0.69	0.81	0.66	0.82
ψ^I	capital adjustment costs	G	20.00	5.00	29.80	29.48	33.56	36.08	27.31
Γ	steady-state capital net worth ratio	SG	1.50	0.05	1.47	1.47	1.47	1.47	1.47
ς	entrepreneurs' bankruptcy rate	B	0.025	0.005	0.031	0.029	0.029	0.029	0.027
χ	financial accelerator	G	0.050	0.010	0.038	0.043	0.042	0.040	0.040
Taylor rule									
ρ	interest rate smoothing	B	0.50	0.20	0.86	0.70	0.66	0.68	0.72
β_π	inflation weight	SG	1.50	0.20	1.94	1.83	1.99	2.00	1.67
Θ_y	output gap weight	G	0.50	0.20	0.12	0.20	0.21	0.23	0.18
AR parameters									
ρ_{UIP}	debt-elastic risk premium	B	0.50	0.20	0.69	0.67	0.80	0.77	0.77
ρ_{LOP}	law of one price gap	B	0.50	0.20	0.86	0.72	0.86	0.83	0.82
ρ_{NW}	entrepreneurs' net worth	B	0.50	0.20	0.54	0.57	0.55	0.52	0.42
ρ_Y	domestic productivity	B	0.50	0.20	0.10	0.05	0.13	0.65	0.07
VAR parameters									
$\rho_{y^*y^*}$	interaction of y_t^* and y_{t-1}^*	B	0.80	0.10	0.90	0.89	0.89	0.89	0.79
$\rho_{\pi^*\pi^*}$	interaction of π_t^* and π_{t-1}^*	B	0.20	0.05	0.20	0.20	0.20	0.20	0.19
$\rho_{r^*r^*}$	interaction of r_t^* and r_{t-1}^*	B	0.60	0.20	0.60	0.56	0.56	0.54	0.86
$\rho_{y^*\pi^*}$	interaction of y_t^* and π_{t-1}^*	N	0.00	0.50	0.51	0.44	0.47	0.44	0.11
$\rho_{y^*r^*}$	interaction of y_t^* and r_{t-1}^*	N	0.00	0.50	-0.49	-0.65	-0.50	-0.60	0.58
$\rho_{\pi^*y^*}$	interaction of π_t^* and y_{t-1}^*	N	0.00	0.50	0.18	0.15	0.14	0.13	-0.02
$\rho_{\pi^*r^*}$	interaction of π_t^* and r_{t-1}^*	N	0.00	0.50	-0.74	-0.66	-0.57	-0.57	0.32
$\rho_{r^*y^*}$	interaction of r_t^* and y_{t-1}^*	N	0.00	0.50	0.05	0.06	0.06	0.06	0.02
$\rho_{r^*\pi^*}$	interaction of r_t^* and π_{t-1}^*	N	0.00	0.50	0.04	0.04	0.04	0.04	-0.02
$\sigma_{\pi^*y^*}$	interaction of $\varepsilon_t^{\pi^*}$ and $\varepsilon_t^{y^*}$	N	0.50	0.25	0.14	0.15	0.15	0.15	0.35
$\sigma_{r^*y^*}$	interaction of $\varepsilon_t^{r^*}$ and $\varepsilon_t^{y^*}$	N	0.30	0.15	0.10	0.09	0.09	0.09	0.09
$\sigma_{r^*\pi^*}$	interaction of $\varepsilon_t^{r^*}$ and $\varepsilon_t^{\pi^*}$	N	0.00	0.50	-0.05	-0.04	-0.05	-0.05	0.02
Std of shocks									
σ_{UIP}	debt-elastic risk premium	IG	1.00	∞	1.39	1.65	1.46	1.49	1.41
σ_{LOP}	law of one price gap	IG	1.00	∞	5.99	5.94	7.92	7.28	8.10
σ_{NW}	entrepreneurs' net worth	IG	1.00	∞	3.01	6.75	3.40	3.98	2.66
σ_Y	domestic productivity	IG	1.00	∞	4.81	4.74	2.64	2.52	2.75
σ_{MP}	monetary policy	IG	0.10	∞	1.08	1.24	1.21	1.30	1.07
σ_{y*}	foreign output	IG	0.50	∞	0.53	0.53	0.54	0.53	0.57
σ_{r*}	foreign inerest rate	IG	0.10	∞	0.05	0.05	0.05	0.05	0.09
$\sigma_{\pi*}$	foreign inflation rate	IG	0.20	∞	0.23	0.23	0.23	0.23	0.50

Source: Author.

Most of the parameters are estimated to be very similar in all the Visegrád economies, but there are also some interesting differences. Overall, the results confirm the widely recognized similarity of the Czech and Slovak economies. While most of the posterior estimates differ by less than one standard deviation, there are a few exceptions.

The posterior estimates of the economy of the euro area show stronger habit of consumption Υ, which is to be expected in the more developed western economies. The values of posterior mean are in line with the literature, for example Tonner and Vašíček (2011) report the value of 0.59 for the Czech economy.

The estimates of inverse elasticity of labour supply Ψ suggest non-elastic labour supply. The estimates are again in line with results reported by Vašíček (2011). The parameter of inverse elasticity of labour supply Ψ is estimated to be slightly lower in the Czech economy, which correlates to a lower natural rate of unemployment and more flexible labour market than in the remaining Visegrád economies. However, the estimate of this parameter for the euro area economy is even lower, which suggests even higher degree of labour market flexibility. This might be surprising, given the unfavourable development in the labour markets of the southern member states of the euro area since the Great Recession that lead to a significant and persistent rise of the unemployment rate.

Schmitt-Grohé and Uribe (2003) suggest values around 0.01 for the debt elastic risk premium parameter Ψ^B. Our estimates are slightly higher, but can still be considered plausible. The lower debt-elastic risk premium elasticity Ψ^B in the Czech economy than in the remaining Visegrád economies suggests that forex dealers are less sensitive about the external balance of the Czech economy in relation to the exchange rate, which correlates to its status of regional safe haven for investors. This probably results from the transparent monetary policy of the CNB and relatively tight fiscal policy. The estimate for the euro area is even lower, which is to be expected because of the reserve status of the euro currency and much deeper forex market. The elasticity of the foreign bond risk-premium with respect to external position Ψ^B is estimated to be more than twice as large in Slovakia as in the Czech Republic, and three times as large as the estimate for the euro area. This result reflects the higher sensitivity of foreign creditors to developments in the relatively small and volatile Slovak economy, and the strong appreciation of the Slovak koruna during the pre-crisis economic boom.

The estimates of the elasticity of substitution between domestic and foreign goods η are overall slightly higher than 0.465 that was reported by Shaari (2008). Nevertheless, Tonner and Vašíček (2011) reported rather higher value of 0.7 for the Czech economy. The elasticity of substitution between domestic and foreign goods η is estimated to be slightly higher in Slovakia, which implies a higher sensitivity of consumers to the price differential between these two types of goods. The elasticity of substitution between home and foreign goods η is estimated to be lower in the euro area than in the Czech or Slovak economies, implying lower consumer sensitivity to price differentials.

The estimates of the price indexation parameter κ are in line with Tonner and Vašíček (2011), who found the estimate of 0.26. Also, Ryšánek *et al.* (2011) found values of price indexation near 0.3. The lower price indexation to past inflation κ in the Czech economy than in the remaining NEV economies is probably caused by the higher and more volatile inflation in Poland and Hungary. The degree of price indexation κ is estimated to be lower in the euro area than in the Czech economy, which can be related to a historically more stable development of the inflation rate.

Table 5.3: Posterior means comparison (relative to CZ)

Parameter		Distrib.	CZ Postrerior	Posteriors relative to CZ SK	PL	HU	EA
Υ	habit persistence	B	0.59	0.96	0.98	1.00	1.12
Ψ	inverse elasticity of labour supply	G	1.24	1.09	1.05	1.08	0.95
ψ^B	elasticity of debt-elastic risk premium	G	0.02	2.33	1.83	2.23	0.72
η	home and foreign goods elasticity of substitution	G	0.60	1.24	0.97	0.99	0.76
κ	price indexation	B	0.27	0.86	1.35	1.39	0.78
γ	preference bias to foreign goods	B	0.29	1.19	0.73	0.81	0.71
θ_H	home goods Calvo parameter	B	0.81	0.92	0.97	0.86	1.01
θ_F	foreign goods Calvo parameter	B	0.79	0.87	1.02	0.83	1.03
ψ^I	capital adjustment costs	G	29.80	0.99	1.13	1.21	0.92
Γ	steady-state capital net worth ratio	SG	1.47	1.00	1.00	1.00	1.00
ς	entrepreneurs' bankruptcy rate	B	0.031	0.935	0.934	0.935	0.871
χ	financial accelerator	G	0.038	1.135	1.113	1.065	1.056
Taylor rule							
ρ	interest rate smoothing	B	0.86	0.81	0.76	0.79	0.84
β_π	inflation weight	SG	1.94	0.94	1.03	1.03	0.86
Θ_y	output gap weight	G	0.12	1.73	1.79	1.97	1.52
AR parameters							
ρ_{UIP}	debt-elastic risk premium	B	0.69	0.97	1.16	1.12	1.11
ρ_{LOP}	law of one price gap	B	0.86	0.84	1.01	0.97	0.96
ρ_{NW}	entrepreneurs' net worth	B	0.54	1.05	1.00	0.96	0.78
ρ_Y	domestic productivity	B	0.10	0.55	1.32	6.82	0.75
VAR parameters							
$\rho_{y^*y^*}$	interaction of y_t^* and y_{t-1}^*	B	0.90	0.99	0.99	0.99	0.88
$\rho_{\pi^*\pi^*}$	interaction of π_t^* and π_{t-1}^*	B	0.20	0.97	0.98	0.97	0.93
$\rho_{r^*r^*}$	interaction of r_t^* and r_{t-1}^*	B	0.60	0.93	0.93	0.90	1.44
$\rho_{y^*\pi^*}$	interaction of y_t^* and π_{t-1}^*	N	0.51	0.86	0.92	0.86	0.21
$\rho_{y^*r^*}$	interaction of y_t^* and r_{t-1}^*	N	-0.49	1.32	1.03	1.23	-1.18
$\rho_{\pi^*y^*}$	interaction of π_t^* and y_{t-1}^*	N	0.18	0.83	0.81	0.74	-0.12
$\rho_{\pi^*r^*}$	interaction of π_t^* and r_{t-1}^*	N	-0.74	0.90	0.77	0.77	-0.44
$\rho_{r^*y^*}$	interaction of r_t^* and y_{t-1}^*	N	0.05	1.12	1.13	1.20	0.31
$\rho_{r^*\pi^*}$	interaction of r_t^* and π_{t-1}^*	N	0.04	0.90	1.03	0.90	-0.41
$\sigma_{\pi^*y^*}$	interaction of $\varepsilon_t^{\pi^*}$ and $\varepsilon_t^{y^*}$	N	0.14	1.06	1.11	1.12	2.56
$\sigma_{r^*y^*}$	interaction of $\varepsilon_t^{r^*}$ and $\varepsilon_t^{y^*}$	N	0.10	0.97	0.96	0.95	0.89
$\sigma_{r^*\pi^*}$	interaction of $\varepsilon_t^{r^*}$ and $\varepsilon_t^{\pi^*}$	N	-0.05	0.95	1.00	0.96	-0.39
Std of shocks							
σ_{UIP}	debt-elastic risk premium	IG	1.39	1.18	1.05	1.07	1.01
σ_{LOP}	law of one price gap	IG	5.99	0.99	1.32	1.22	1.35
σ_{NW}	entrepreneurs' net worth	IG	3.01	2.24	1.13	1.32	0.88
σ_Y	domestic productivity	IG	4.81	0.98	0.55	0.52	0.57
σ_{MP}	monetary policy	IG	1.08	1.15	1.12	1.20	0.99
σ_{y*}	foreign output	IG	0.53	0.99	1.00	0.99	1.07
σ_{r*}	foreign inerest rate	IG	0.05	0.99	0.99	0.99	1.66
$\sigma_{\pi*}$	foreign inflation rate	IG	0.23	1.00	1.00	1.00	2.16

Source: Author.

The differences in preference bias to foreign goods γ can be explained by the greater openness of the export-oriented Czech and Slovak economies in comparison to the larger and relatively self-sustaining Polish economy and the economy of the euro area. In terms of the exports to GDP ratio, the Hungarian economy is actually more open than the economy of the Czech Republic. However, given the large share of foodstuffs in the consumption basket of the households, the estimate may be influenced by the relatively self-sufficient agricultural sector in Hungary and relatively large share of imported groceries in the Czech economy.

The posterior estimates of the Calvo parameters suggest an average duration of the home and foreign goods prices between three and five quarters. Obtained results are in accordance with Shaari (2008) and Christensen and Dib (2008) who found values near 0.75 as well. However, Tonner and Vašíček (2011) reported lower price rigidity in the Czech economy with Calvo parameters of home and foreign goods of 0.52 and 0.64 respectively. The Calvo parameters are estimated to be nearly the same for the Czech Republic, Poland and the euro area. In the Slovak and Hungarian economies, the estimates are somewhat lower, suggesting greater flexibility of prices. Lower estimates of the Calvo parameters in the Slovak economy may be explained by the adoption of the euro currency and the subsequent period of transition and also by the fact that, in the currency union, firms need to update their prices more often in order to remain competitive as compared to an economy with an independent national currency.

Our posterior estimates of the capital adjustment costs Ψ^I are somewhat higher than 23.6 obtained by Christensen and Dib (2008). However, the uncertainty related to this parameter is substantial and so the posterior estimates can be considered plausible. Higher capital adjustment costs Ψ^I in Hungary and Poland suggest lower investment efficiency. The Czech and Slovak estimates are very similar to each other and slightly lower than in the remaining Visegrád economies, implying higher investment efficiency. The estimate for the euro area is the lowest. The estimates of this parameter are connected to the underlying volatility of the observed real investment. In the Visegrád economies, that are much smaller than the euro area, the development of macroeconomic aggregates is more volatile and the estimates of the capital adjustment costs are expected to be larger.

The parameters of financial frictions are estimated to be nearly the same in all the examined economies. This may be explained by the fact that most commercial banks operating in these economies are subsidiaries of large international groups, which treat the CEE (Central and Eastern Europe) markets in a similar way, and that the regulatory framework in the European union is to a large extent homogeneous. The posterior estimates of the capital/net worth steady-state ratio Γ roughly correspond to the debt-equity ratio of non-financial corporations; see European Central Bank (2012). The generally more stable environment of the euro area is reflected in the somewhat lower posterior estimate of the steady-state bankruptcy rate ς. The estimated bankruptcy rate implies an average entrepreneurs' business lifespan of eight to nine years. Tonner and Vašíček (2011) calibrated this parameter to the value of 0.9728, which would imply the business lifespan of approximately nine years. Financial accelerator parameter χ is estimated closer to the upper bound of the values reported in the literature. Shaari (2008) obtained an estimate of 0.032, Christensen and Dib (2008) obtained a value of 0.042, while Tonner and Vašíček (2011) reported a value of 0.0269 for the Czech economy.

The estimated parameters of the Taylor rule correspond to the fact that the central banks in the examined economies operate independently[6] in more or less strict inflation

[6]In case of Slovakia, the National Bank of Slovakia exercised independent monetary policy until the adoption of the common european currency in January 2009.

targeting regimes. There are several interesting differences in the estimates of the Taylor rule parameters. While the interest rate smoothing parameter ρ is estimated to be the highest in the Czech economy, the weight of the output gap Θ_y in the Czech economy is estimated to the lowest. This suggests that the Czech National Bank is more focused on its primary goal of attaining price stability than the remaining central banks in the Visegrád economies, that take the output gap into consideration more noticeably. At the same time, the changes of the policy interest rate of the Czech National Bank are mostly implemented in a gradual manner. For example in the Hungarian or Polish economy, the central bank has to adjust the policy rates more vigorously and the smoothing of policy rate is less apparent. The similarity of the Taylor rule parameters of the European Central Bank and the National Bank of Slovakia is to be expected, due to the convergence of monetary policy after entering the ERM II exchange rate mechanism.

The posterior estimates of the Slovak economy are comparable to the values obtained by Senaj et al. (2010), who estimated a two-country DSGE model for Slovakia and the euro area. It is also worth mentioning that quite often the estimates of the structural parameters of the Czech economy are closer to the estimates of the euro area than those of Slovakia, even though it is Slovakia that is a member of the euro area. This suggests that the Slovak economy is rather specific in certain aspects in comparison with the euro area as a whole.

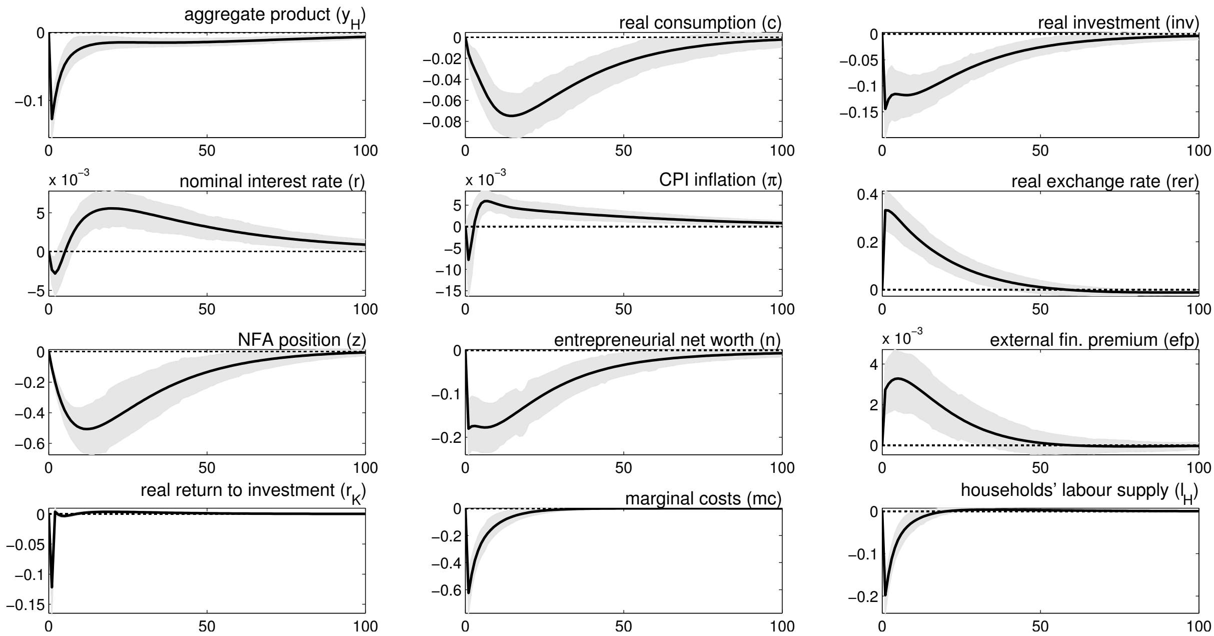
Estimates of AR(1) parameters show high persistence of law of one price gap shock and debt-elastic risk premium shock. Shock in entrepreneurial net worth is significantly less persistent and the domestic productivity shock is identified as transient. Estimated standard deviations of innovations of these exogenous processes display high volatility of law of one price shock, net-worth shock and domestic shock in productivity. Debt-elastic risk premium shock and monetary policy shock are estimated to be less volatile.

Estimated parameters of foreign VAR(1) block suggest quite high persistence of foreign output and high volatility of foreign inflation. In the Visegrád economies, the negative parameters of the VAR(1) block $\rho_{y^*r^*}$ and $\rho_{\pi^*r^*}$ capture the transmission mechanism in the foreign economy (represented by the euro area). The higher the interest rate in last period, the lower the inflation and the output in the present. However, in the euro area economy model, there is no clear transmission in the foreign economy (represented by the U.S. economy in this case). Similarly, the positive estimates of parameters $\sigma_{\pi^*y^*}$ and $\sigma_{r^*y^*}$ show positive correlation of the innovations in foreign output and foreign inflation and of the innovations in foreign output and foreign interest rate. Small negative posterior mean of $\sigma_{r^*\pi^*}$ suggests negative correlation of the innovations in foreign interest rate and foreign inflation.

5.3 Impulse response functions

Impulse response functions describe reactions of endogenous model variables to exogenous shock innovations. This allows us to see the basic mechanism of model's behaviour. In this section I describe the baseline impulse responses of the Czech economy model and discuss the most distinct specifics of the behaviour of the remaining examined economies. Only the graphs depicting the impulse responses of the Czech economy model are included in this section. Graphs that compare the impulse responses of the remaining examined economies to the responses of the Czech economy model are included in the Appendix C, section C.4. Impulse responses to the innovations of one standard deviation of given shock are reported. Impulse responses are expressed as steady state percentages of particular variables. Mean estimates and 95 % HDP intervals are depicted in the graphs.

Figure 5.3: Impulse responses to law of one price gap shock, CZ

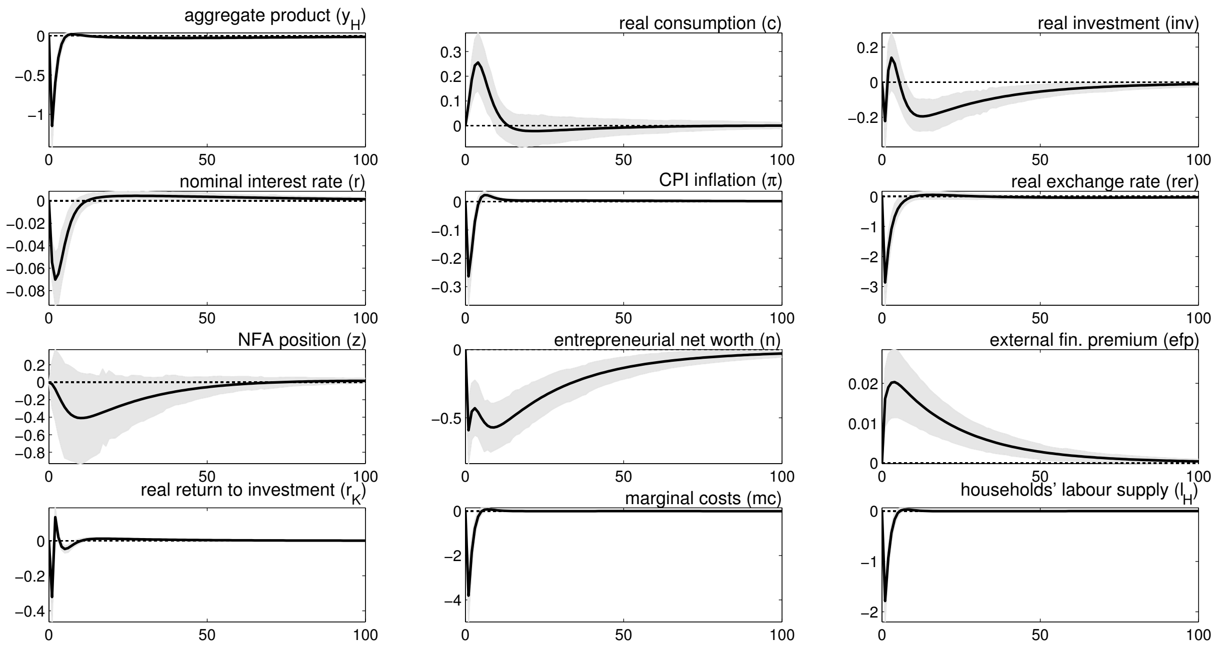


Source: Author.
Note: Per cent deviations caused by 1% shock are depicted.

Figure 5.3 depicts the impulse responses of the Czech economy to the innovation in the law of one price gap. Since the law of one price gap is defined as a difference between the foreign prices expressed in domestic currency and the retail prices of imported goods, an increase of the law of one price gap means that the retail prices decline relative to the foreign prices, the gap closes and the profit margin of retailers declines. This causes a short disinflation of foreign goods prices and consequently also consumer prices. In the medium term, the prices return to their steady state which generates mild inflation. Lower profit margin causes the retailers to operate with lower profits, which results in lower transfers to households. Households smooth their consumption in time and so they adjust their consumption downwards only gradually. Due to relatively high elasticity of substitution between domestic and foreign goods, the domestic import demand grows, which leads to a deterioration of the trade balance and the net foreign assets position declines. The declining competitiveness is partially compensated through nominal and real exchange rate depreciation. Therefore, the increase of the law of one price gap causes a decline aggregate product and its components, as well as a decline of the domestic marginal costs, wages and gross rental rate of capital. This causes a decline in the real price of capital and consequently in the demand for investment. The downswing in the real price of capital as a manifestation of a decline of the profitability of the domestic firms causes a loss of entrepreneurial net worth and increases the external finance premium, which deepens the decline in the net worth. Monetary authority decreases the nominal interest rate at first because of the falling product, but soon it is raised in order to cut down the CPI inflation. While the impulse responses of the Polish and Hungarian economies are virtually the same as those of the Czech economy, the impulse responses of the Slovak economy are slightly less persistent and the responses of the euro area economy are slightly more persistent.

In figure 5.4, the impulse responses of the Czech economy to the innovation in the debt-elastic risk premium shock are depicted. Positive innovation in the UIP shock causes a decline in the risk premium and an appreciation of the real exchange rate. This induces higher demand for imported goods and causes a growth of real consumption and investment. Foreign demand for domestic exports, however, declines and so do the net exports, aggregate product and also the net foreign assets position. Declining prices of foreign goods bring about a deflation of consumer prices. The monetary authority reacts to the downturn in the aggregate product and CPI deflation by a cut in nominal interest rate. Appreciation of real exchange rate causes a decrease of domestic marginal costs, wages and capital rental rate. Due to increased domestic import demand and decreased foreign export demand, the profitability of domestic firms declines together with the net worth and the capital stock, which leads to an increase of the external finance premium. As the real exchange rate depreciates, the situation returns to the steady state. In the remaining Visegrád economies, the net foreign assets position deteriorates more strongly than in the Czech economy and also the magnitude of the reaction of the monetary authority necessary in order to stabilize the economy is estimated to be significantly larger than in the Czech economy. In the economy of the euro area, the effect of real exchange rate appreciation on the net foreign assets is rather surprising. Due to a relatively low elasticity of substitution between domestic and foreign goods, the effect of real exchange rate change on the volumes is dominated by the nominal effect in the net foreign assets position (the nominal value of imports expressed in domestic currency declines).

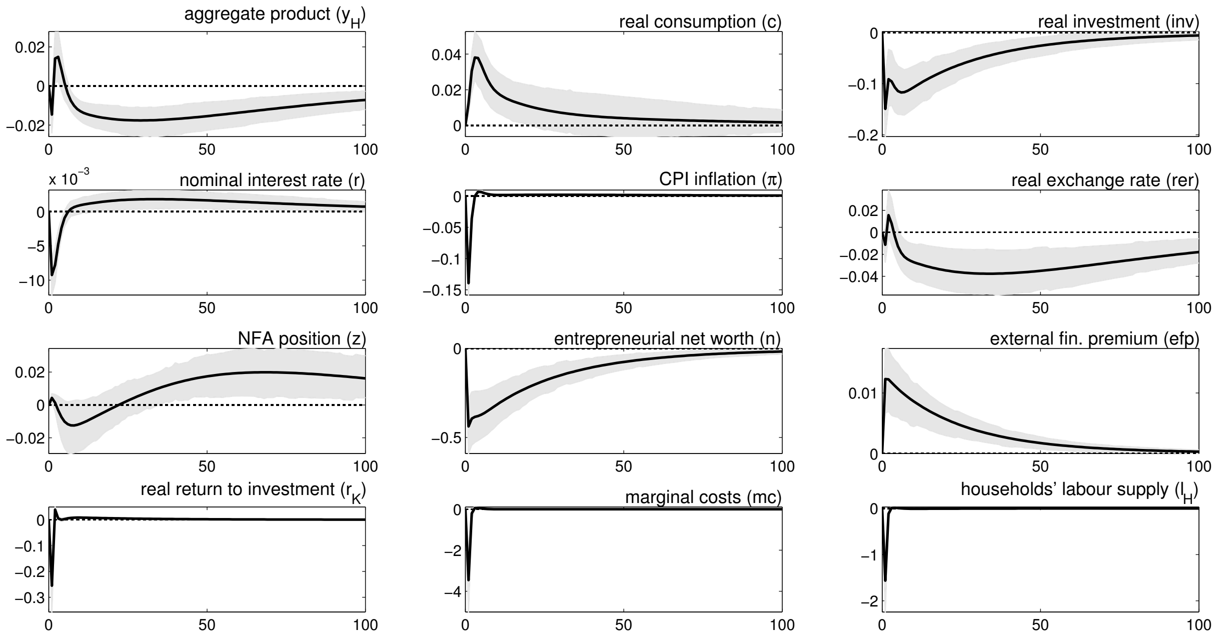
Figure 5.4: Impulse responses to debt-elastic risk premium shock, CZ



Source: Author.
Note: Per cent deviations caused by 1% shock are depicted.

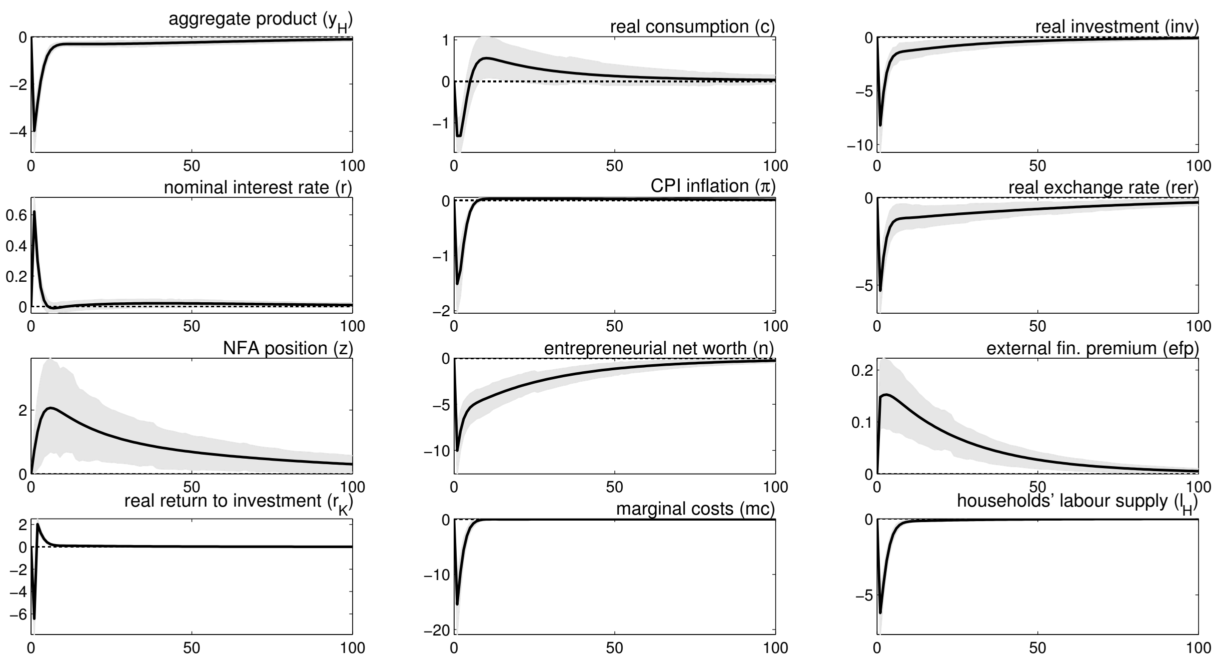
Figure 5.5 shows the impulse responses of the Czech economy to the innovation in the domestic productivity shock. The shock in domestic productivity causes a decline of marginal costs, wages and capital rental rate. Demand for labour and capital decreases and the real price of capital declines together with real investment. Lower real price of capital and higher real interest rate than was previously expected bring about a downturn in entrepreneurial net worth and that increases the external finance premium. The aggregate product declines at first due to the drop in investment, but as the goods prices decline the consumption demand grows and the product gets above the potential. Impulse responses of the Slovak economy to this shock are identified very similarly to those of the Czech economy. The responses of the remaining economies are more heterogeneous, differing in the reaction of the monetary authority and real exchange rate response.

Figure 5.5: Impulse responses to productivity shock, CZ



Source: Author.
Note: Per cent deviations caused by 1% shock are depicted.

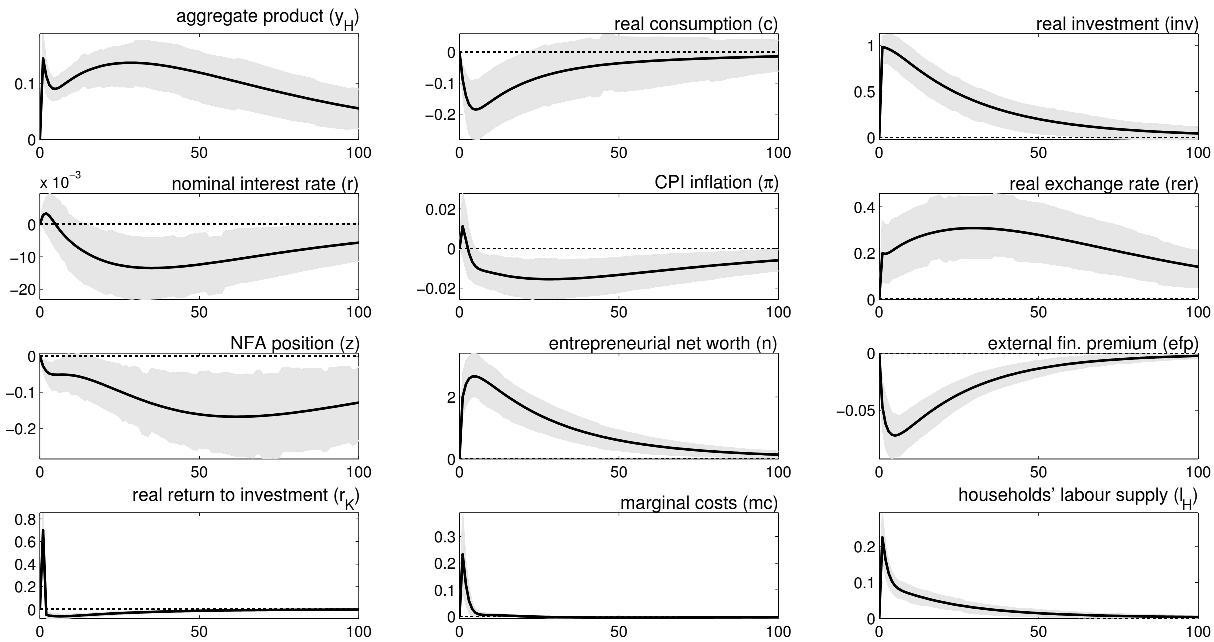
Figure 5.6: Impulse responses to monetary policy shock, CZ



Source: Author.
Note: Per cent deviations caused by 1% shock are depicted.

In figure 5.6, the impulse responses of the Czech economy to the monetary policy shock are depicted. Positive shock in the nominal policy interest rate causes a contraction of the economy. Demand for consumption declines together with aggregate output and CPI price level. The deflation causes higher real financing costs of entrepreneurs' debts and lower real return to investment. Therefore, the entrepreneurial net worth declines and external finance premium rises. Real price of capital and investment demand fall because of high expected financing costs in the future. High nominal interest rate also induces real exchange rate appreciation, which supports the domestic demand for foreign imports and decreases the foreign demand for domestic exports. The adjustment of the domestic consumption is rather sluggish and so the drop in the investment demand outweighs the effect of real exchange rate appreciation. Together with the nominal effect on the value of imports expressed in domestic currency these two factors cause the net foreign assets position to improve. The impulse responses to the monetary policy shock are rather homogeneous across all the examined economies with the main differences arising in the response of the net foreign assets and external finance premium. The magnitude of the impulse responses of the euro area economy differs slightly in comparison with the responses of the Czech economy, however the sense of the responses and their interpretation remains valid.

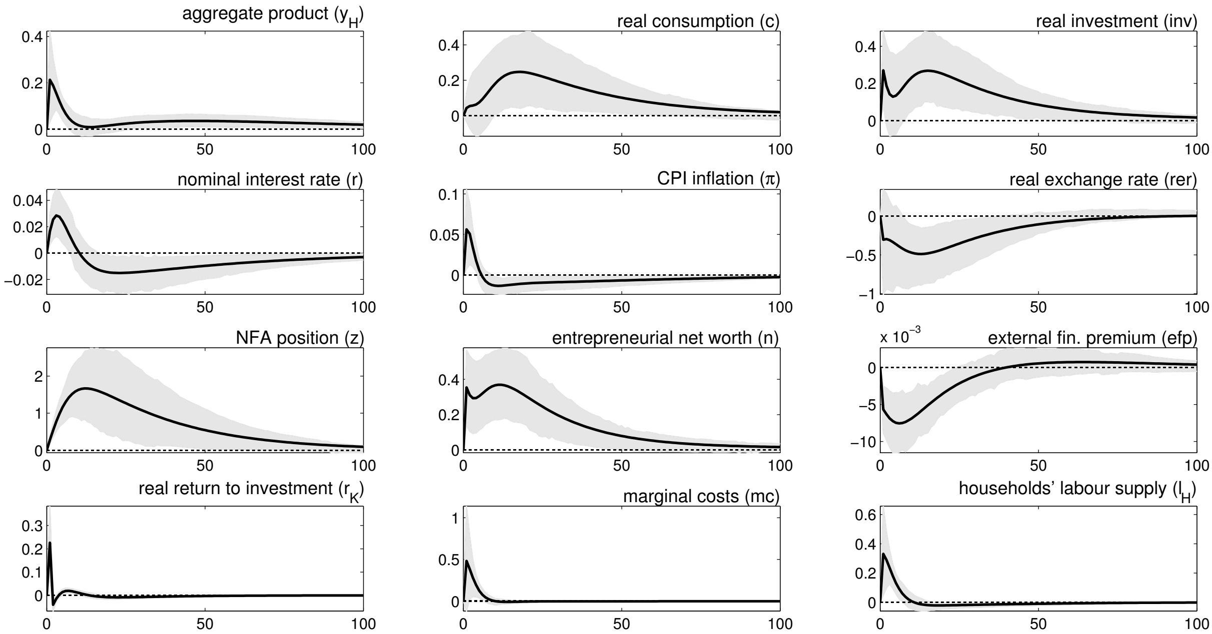
Figure 5.7: Impulse responses to net worth shock, CZ



Source: Author.
Note: Per cent deviations caused by 1% shock are depicted.

Figure 5.7 contains the impulse responses of the Czech economy to the innovation in the net worth shock. This shock causes that the effective survival rate of the entrepreneurs gets above the steady state. Put in another way, the entrepreneurs receive extra net worth. Due to the law of motion of the entrepreneurial net wort, the effects of the net worth shock are quite persistent. The entrepreneurs' leverage ratio and therefore also the external finance premium decline. The financing costs of capital investment decreases and the real price of capital and the demand for investment increase. Capital stock and the aggregate output grow as well. Growing capital stock and labour supply decrease the capital rental rate and households' wages, therefore, the marginal costs decline at first. This induces mild CPI deflation, decline of nominal policy interest rate and real exchange rate depreciation. High investment demand outweighs the effects of real exchange rate depreciation on net exports and the net foreign assets position deteriorates. The effects of the net worth shock are significantly stronger in the Slovak economy, while in the Polish and Hungarian economies, the responses are only slightly more pronounced than in the case of the Czech economy. In the euro area economy, the size of the responses to the net worth shock in comparison to the Czech economy varies.

Figure 5.8: Impulse responses to foreign output shock, CZ

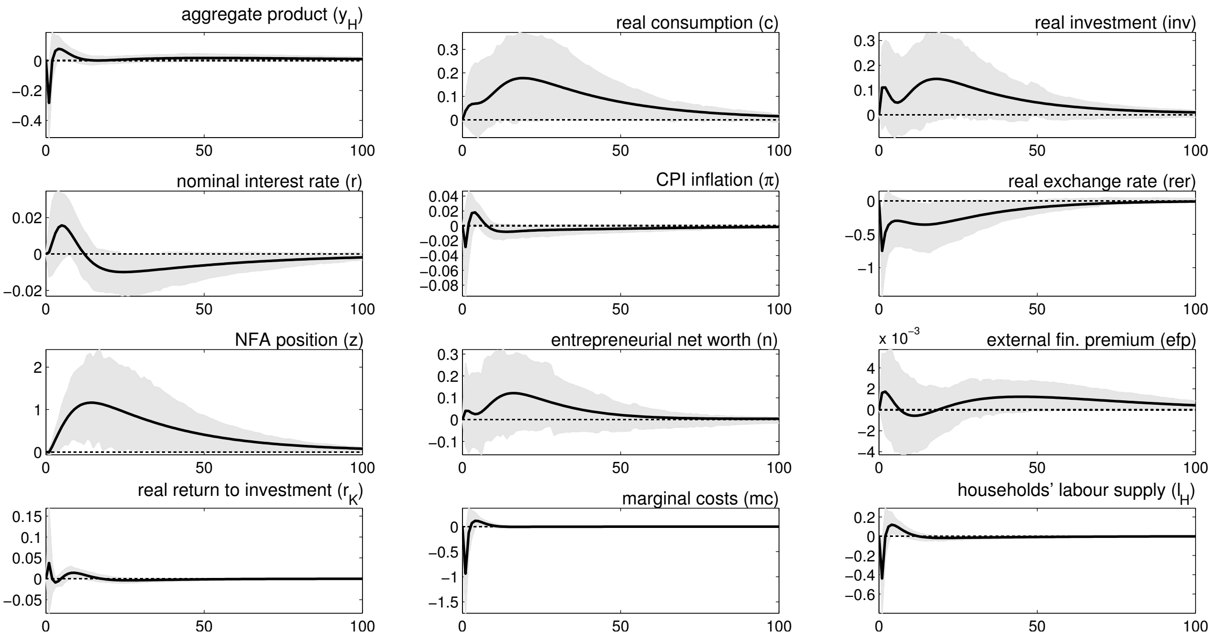


Source: Author.
Note: Per cent deviations caused by 1% shock are depicted.

Impulse responses of the Czech economy to the innovation in the foreign output are included in the figure 5.8. High foreign demand boosts the net exports and so the net foreign assets position improves significantly. Aggregate product, real consumption and real investment are all stimulated by increased foreign demand. Growing marginal costs induce mild CPI inflation that is countered by an increase of nominal interest rate. The real exchange rate appreciates due to increased interest rate and weakens the effects of foreign demand on the net exports. The profitability of the domestic firms improves and causes a growth of entrepreneurial net worth and a decline of external finance premium. Also, the real price of capital grows with the increased investment demand, which further stimulates real return to capital investment. The impulse responses to the foreign demand shock are relatively homogeneous across the Visegrád economies, while in the euro area economy, the responses are noticeably more persistent.

Figure 5.9 depicts the impulse responses of the Czech economy to the innovation in foreign inflation. This shock causes a decline in domestic demand for foreign imports and increases foreign demand for domestic exports. However, it also causes an appreciation of the real exchange rate. The real net exports slightly decline initially but the net foreign assets position improves due to the nominal effect on the value of imports. Medium-term effect of this shock on the real aggregate product is positive. Increased investment demand leads to a growth of entrepreneurial net worth. The external finance premium fluctuates as the rates of growth of capital stock and entrepreneurial net worth differ. The sense of the impulse responses is the same in all the examined economies. In the remaining Visegrád economies, the effects of the foreign inflation shock are generally slightly less pronounced than in the case of the Czech economy. Impulse responses of the euro area economy are more persistent.

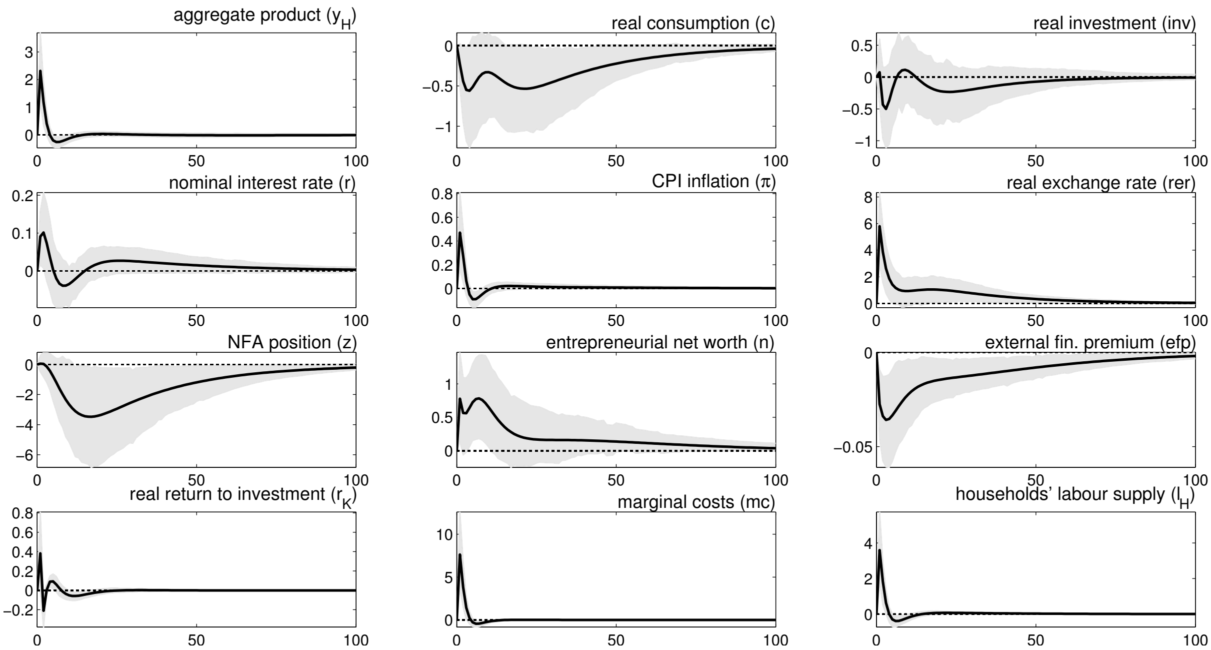
Figure 5.9: Impulse responses to foreign inflation shock, CZ



Source: Author.

Note: Per cent deviations caused by 1% shock are depicted.

Figure 5.10: Impulse responses to foreign interest rate shock, CZ



Source: Author.

Note: Per cent deviations caused by 1% shock are depicted.

In figure 5.10, the impulse responses of the Czech economy to the innovation in foreign interest rate are depicted. This shock causes real exchange rate depreciation and stimulates the demand for domestic exports. Net foreign assets position deteriorates due to the nominal effect, as the value of imports expressed in domestic currency increases. Increased aggregate product implies higher marginal costs and a CPI inflation. The inflation is countered by an increase of nominal policy interest rate. The inflation causes positive real return to capital investment, a growth of entrepreneurial net worth and a decline of the leverage ratio and external finance premium. The sense of the impulse responses is the same across the Visegrád economies with slight differences in the magnitude of the responses of some variables, mainly the net foreign assets position. Qualitatively different impulse responses of the euro area economy are given by the different estimates of the foreign SVAR(1) block.

Generally, we can say that the financial accelerator mechanism intensifies the effects of the exogenous shocks on the real economic activity via entrepreneurial net worth and investment demand.

Overall, the impulse responses of the Visegrád economies to the exogenous shocks are identified very similarly with slight differences in the magnitude of the response of some variables, most notably the net foreign assets position and to a smaller extent also the real exchange rate. Otherwise, the sense of the impulse responses is the same. The impulse responses of the euro area economy differ from those of the Visegrád economies in several aspects. Often, the impulse responses of the euro area economy are noticeably more persistent. And also, due to a qualitatively different estimates of the foreign SVAR(1) block parameters, which may be related to the different role of the euro currency in the world economy, some impulse responses differ even qualitatively. Impulse responses of the euro area economy to the foreign interest rate shock being the most striking example.

5.4 Filtered shock innovations

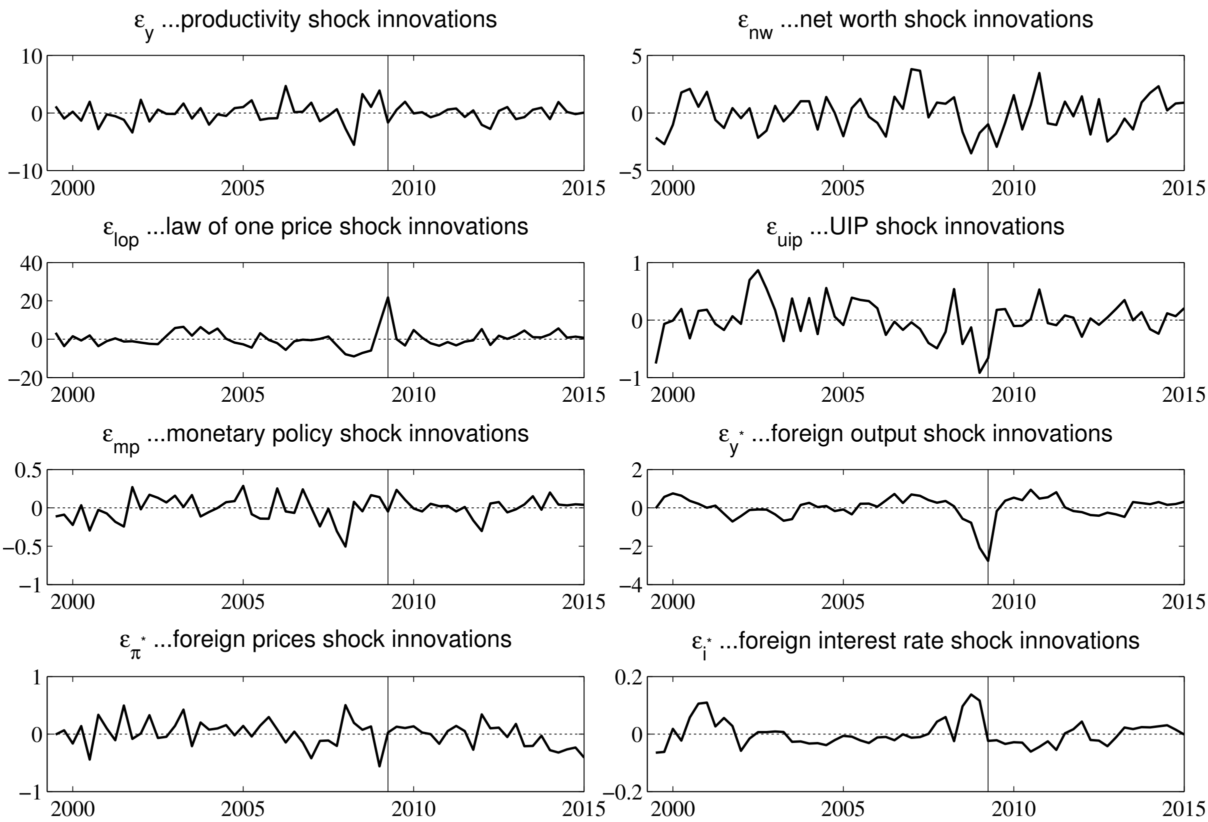
In this section, the filtered innovations of exogenous shocks as identified by the nonlinear particle filter are discussed. Graph 5.11 displays the shock innovations identified in the Czech economy. Graphs depicting the shock innovations in the remaining economies are included in the Appendix C, section C.5.

Filtered shock innovations show the turbulent period of the Great Recession as alike in all the examined economies. A strong negative shock came from the external environment via negative innovations in foreign output and as a result the foreign demand for domestic exports dropped. The downturn in the foreign demand is identified earlier in the model of the euro area, that was hit in the last quarter of 2008. Subsequent contraction of the euro area economy reached the Visegrád economies in the first quarter of 2009. There were also noticeable disinflationary pressures from abroad in the last quarter of 2008. In all the economies a substantial positive innovations closed the law of one price gap as importers lowered their profit margins during the crisis. Negative innovations in entrepreneurial net worth increased the number of bankruptcies during 2008-2009, which exacerbated the recession. The negative innovations in the net worth shock are again identified approximately one quarter earlier in the euro area economy than in the Visegrád economies, which can be related to the mechanism of the underlying financial crisis and spreading contagion in the financial markets.

The large depreciations of the local currencies during the crisis are explained by large negative innovations in the UIP shock at the turn of 2008 and 2009 and relatively loose monetary policy in the Visegrád economies. The biggest negative UIP shock came in the Polish economy, which explains the large currency depreciation there. The depreciation of the Hungarian currency was limited by a relatively restrictive monetary policy, indicated by large positive monetary policy shocks during the crisis. In Slovakia, the situation was apparently even more dramatic due to disturbances related to the euro conversion. The negative innovations of monetary policy shock suggest that the independent monetary policy of the National Bank of Slovakia was relatively loose in the period of economic boom in 2007-2008, which may be explained by the participation in the ERM II mechanism, as the central bank struggled to maintain the exchange rate within the fluctuation band. However, the large positive innovations of the UIP shock in 2006Q4 and 2008Q2 led to appreciation pressures that had to be resolved by adjustment of the central parity. The large negative innovation of the UIP shock in 2008Q4 suggests that the Slovak koruna would probably have also depreciated during the Great Recession had it not been replaced by the euro in 2009. In the euro are, the UIP shock innovations are identified earlier during 2007 and 2008, counteracting the general monetary policy tightening in the pre-crisis period and moderating the appreciation of the euro.

The economic slowdown of 2012 is explained by a downturn of foreign demand and entrepreneurial net worth. The positive innovations of the LOP shock indicate a decline in importers' profit margins. Large negative innovations in the UIP shock explain the depreciation of the Polish zloty and Hungarian forint. According to the monetary policy shock innovations, the relatively loose monetary policy in 2011 tightened during 2012 in these two countries in particular. The development of the net worth shock innovations shows that the Slovak economy went through a very difficult period from the point of view of entrepreneurs between 2009 and 2012 as well. The exchange rate intervention of the CNB is captured as a negative innovation of the UIP shock at the turn of 2013 and 2014. More recently we can see a series of negative innovations of foreign price shock that translate to disinflationary pressures through import prices. On the other hand, a sequence of positive net-worth shock innovations indicates an improvement in financing availability and explain the pickup in investment.

Figure 5.11: Filtered shock innovations, CZ



Source: Author.

Note: Shock innovations are depicted in per cent, vertical line - 2009Q1.

It is also worth noting the large shocks in the entrepreneurial net worth in Poland and Hungary before their accession to the European Union in 2004. A series of negative net-worth shock innovations in 2001 in Poland corresponds to a period of economic difficulties[7] in the aftermath of the 1998 Russian crisis. After a period of loose monetary policy, monetary policy eventually tightened in order to reduce the macroeconomic imbalances incurred, which led to a plunge in investment in 2001. While the Polish crisis had many internal and external causes, the model explains it in part by net worth shock. Large innovations of net worth shock in 2003 in Hungary can be directly related to the period of instability, when large macroeconomic imbalances caused by expansionary fiscal policy became evident and an open conflict erupted between the government and the central bank on the policy mix. A period of exchange rate turbulence, major policy interest rate hikes and large scale capital outflow ensued.

5.5 Shock decomposition

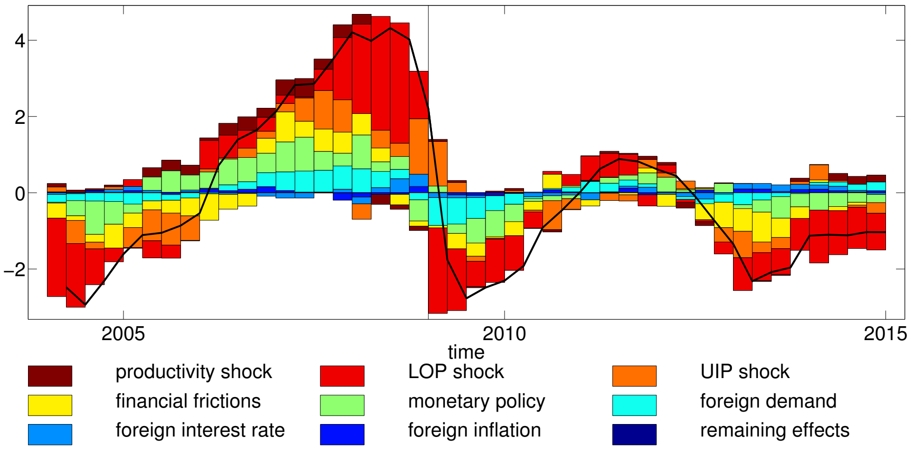
In the following section, the shock decomposition of the main macroeconomic variables is discussed. Namely we focus on the aggregate product, nominal interest rate CPI inflation and real exchange rate. The instrument of shock decomposition allows us to see the effects of particular exogenous shocks on the smoothed variables in time. Graphs 5.12 through 5.16 depict the shock decomposition of real aggregate product in the examined economies. Shock decompositions of the remaining variables are included in the Appendix C, section C.6.

Figure 5.12 shows the shock decomposition of the Czech real aggregate product. We can see that nearly all the exogenous shocks pushed the real product up between 2006 and 2007, with the law of one price shock gaining dominance in 2007-2008. This means that the period of economic boom was brought about by growing foreign demand, loose monetary and financing conditions, relatively weak exchange rate and increasing profitability of the domestic firms, that were able to gradually increase their profit margins due to strengthening demand. By the end of 2008, only the weakening real exchange rate partially softened the blow of the Great Recession, as the profit margins fell sharply, indicating a slump in the aggregate demand. After a weak improvement during 2010 the situation worsened again in 2012, when the combination of worsening profitability of domestic firms, increasing spreads in the financial market and relatively strong real exchange rate darkened the outlook for the Czech economy. After the exchange rate intervention of the CNB, a small positive contribution of the UIP shock can be seen in the shock decomposition. Also, the negative contributions of the financial friction shock vanished by 2014. Nevertheless, according to the negative contribution of the LOP shock, the demand remains weak.

The shock decomposition of the Czech nominal interest rate shows a relatively balanced contributions of the different exogenous shocks. The relative importance appears to be similar as in the case of aggregate output. In case of the CPI inflation, a prominent role of the monetary policy and productivity shocks is confirmed by the shock decomposition. The real exchange rate is mostly driven by the LOP and UIP shocks.

[7]Between 1998 and 2002 the unemployment rate in Poland doubled and reached 20 %. The Polish central bank lowered interest rates in 1998 and 1999 by 11 pp to 13 % due to the prospect of falling inflation. As inflation increased and reached 10 % in 2000, the central bank gradually increased interest rates by a total of 6 pp to 19 %.

Figure 5.12: Shock decomposition of real aggregate output, CZ

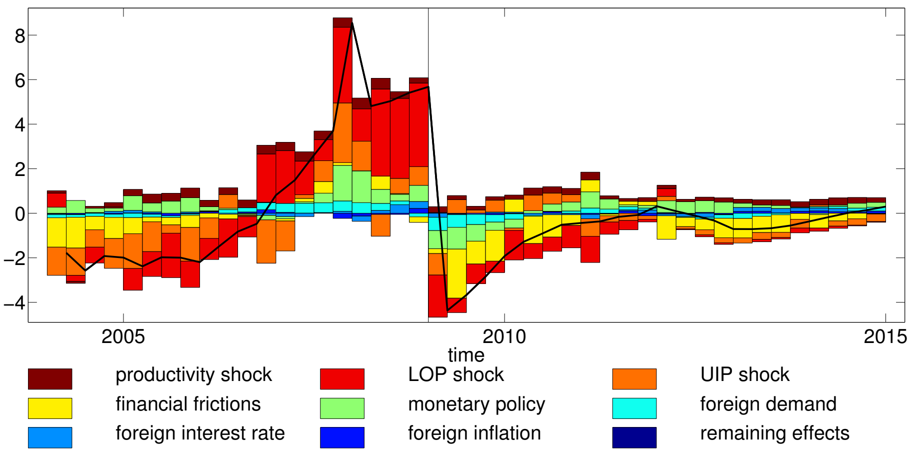


Source: Author.
Note: Per cent deviations are depicted, vertical line - 2009Q1.

Figure 5.13 contains the shock decomposition of the Slovak real aggregate product. The shock contributions during the Great Recession are similar to the Czech case. However, the positive contribution of the exchange rate depreciation during the onset of the crisis is not present in the Slovak case due to the euro adoption in 2009. Otherwise, a stronger influence of the financial frictions shock is apparent. Lately, the Slovak real output remains close to its steady state with the contributions of individual shocks quite small.

The shock decomposition of the remaining Slovak macroeconomic variables shows similar relative importance of the different types of exogenous shocks for their development as in the Czech economy. As in the decomposition of the real output, the decomposition of the real exchange rate shows a decline of volatility after the euro adoption. The CPI inflation is driven mainly by the productivity shock, but the UIP and monetary policy shocks were important in the past as well.

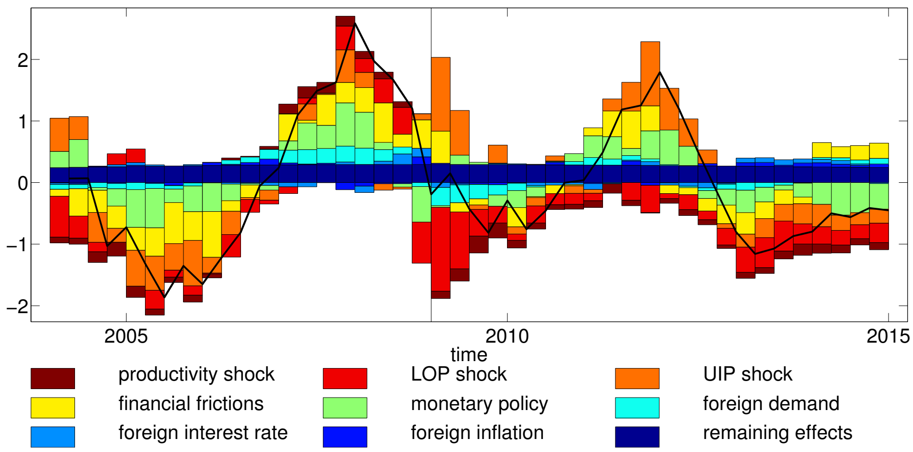
Figure 5.13: Shock decomposition of real aggregate output, SK



Source: Author.
Note: Per cent deviations are depicted, vertical line - 2009Q1.

In the Figure 5.14, the shock decomposition of the Polish real aggregate product is depicted. The graph shows, that the Polish real output increased in the pre-crisis period due to nearly all kinds of the exogenous shocks. Unlike in the Czech or Slovak economies, the upswing was not determined by extraordinary profit margins of domestic firms, but was generated mainly by favourable financing conditions and loose monetary policy. This result can be related to lower openness of the Polish economy to the international trade that prevented a substantial overheating in the pre-crisis period. However, the downturn during the crisis was mainly caused by the law of one price shock, which indicates a weak demand even in the Polish economy in this period. The strong depreciation of the Polish zloty cushioned the negative impact of the crisis considerably. The improvement of the aggregate product in the second half of 2011 and the first half of 2012 was generated by loose monetary policy and another exchange rate depreciation. Recently, the Polish real output remains below its steady state due to relatively tight monetary policy but also unfavourable development of the UIP and LOP shocks. The shock decomposition of the remaining three main Polish macroeconomic variables shows similar composition of the exogenous shocks as in the Czech economy.

Figure 5.14: Shock decomposition of real aggregate output, PL

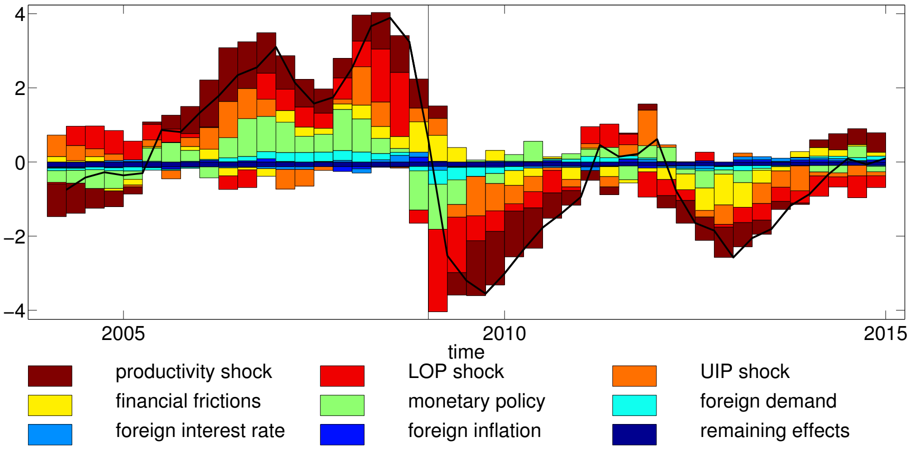


Source: Author.
Note: Per cent deviations are depicted, vertical line - 2009Q1.

In the Figure 5.15, the shock decomposition of the Hungarian real aggregate product is shown. The shock contributions show greater weight of the productivity shock in the Hungarian economy than was the case in the Czech or Slovak economy. During the crisis, the relatively tight monetary policy worsened the real economic downturn. As was the case in other Visegrád economies, the economic contraction is explained mainly by the LOP shock and also by a unfavourable development of real productivity. The economic slowdown in 2012 is explained by negative innovations in the net worth and productivity shocks. In 2014, the contributions of the productivity shock turned positive and became the main factor of economic recovery. The shock decompositions of the nominal interest rate and CPI inflation also indicate greater importance of the productivity shock for their development than was the case in the remaining Visegrád economies described above. Otherwise, the composition of the exogenous shocks is similar to the Czech case.

Figure 5.16 shows the shock decomposition of the real aggregate product of the euro area. Similarly to the Czech economy, the economic boom during 2006-2007 is to a large extent explained by the law of one price shock, indicating increased profit margins of the European firms and strong demand. However, as the economic crisis arrived to the Western European countries by the end of 2008, the positive contribution of the LOP shock vanished. Since 2009, a strong negative pressure caused by the net worth shock is identified in the euro area as the financial sector reacted to the crisis and tightened the financing conditions. In the last quarter of 2014, a relatively large positive contribution of the net worth shock appeared and helped the real output to return to its steady state. The contribution of the monetary policy shock remains slightly negative, as the potential of the conventional monetary policy tools is depleted and the inflation consistently undershoots the target.

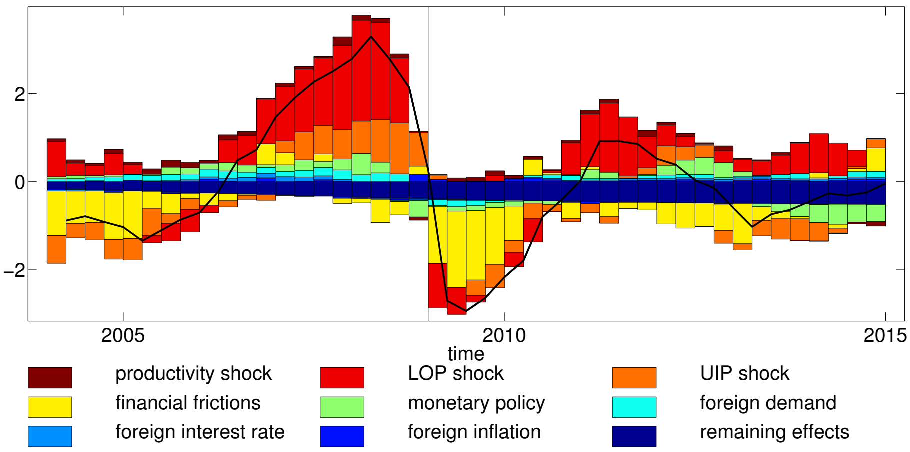
Figure 5.15: Shock decomposition of real aggregate output, HU



Source: Author.
Note: Per cent deviations are depicted, vertical line - 2009Q1.

The shock decomposition showed roughly similar development during the crisis in the four Visegrád economies. The differences in the shock decompositions can be explained by the adoption of the common european currency in the case of Slovakia and by the lower openness to the international trade in the case of Poland. Relatively volatile development of the CPI inflation in the Hungarian economy is reflected in the greater weight of the real productivity shock, its main driver, in the decompositions. The strong influence of the financial frictions shock during the crisis in the case of the euro area economy can be explained by greater integration of the Western European economies in the international financial markets and the spread of the financial contagion and turmoil through these markets in the early phase of the crisis.

Figure 5.16: Shock decomposition of real aggregate output, EA



Source: Author.
Note: Per cent deviations are depicted, vertical line - 2009Q1.

5.6 Filtered variables

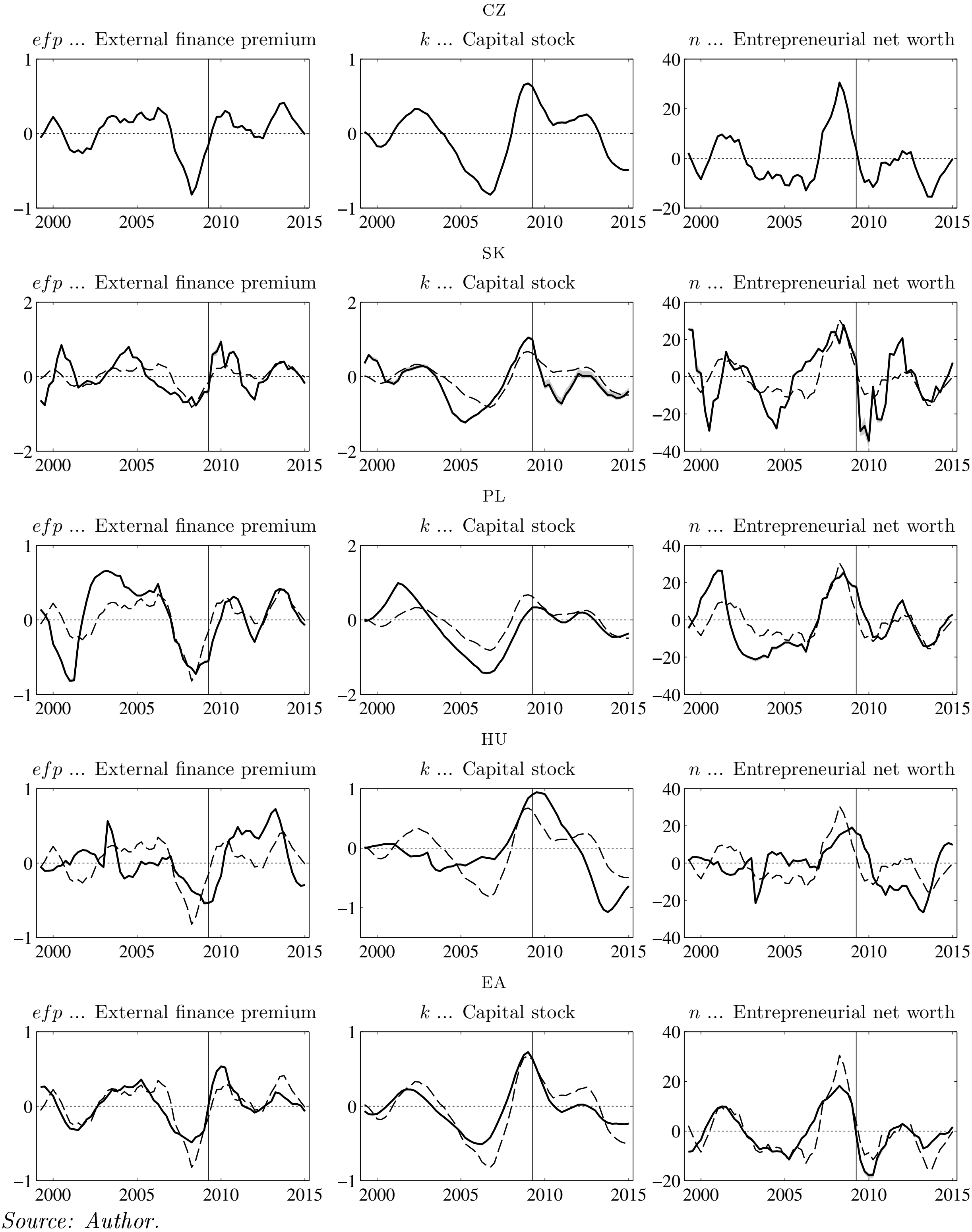
The development of the unobserved variables of the financial market in the Visegrád economies and the economy of the euro area is depicted in Figure 5.17. These graphs aptly illustrate the effects of financial frictions during the Great Recession.

In the favourable period of economic boom between 2006 and 2008, the entrepreneurial net worth of firms increased, which lowered the perceived riskiness of loans and thus lowered external finance premia (interest rate spreads). During the financial crisis of 2008, entrepreneurial net worth decreased at first due to exogenous factors (increased systemic risk and uncertainty) and later also due to the worsening economic conditions, realization of losses, and bankruptcies.

While the pre-crisis increase in entrepreneurial net worth was comparable in the Czech, Slovak and Polish economies, the improvement was less substantial in Hungary and the euro area. The downturn of entrepreneurial net worth after 2008 was estimated to be significantly larger in Slovakia than in the remaining economies. This development may be related to the real exchange rate depreciation of the domestic currencies that occurred in 2009, which somewhat moderated the impact of the crisis on the domestic producers. According to the model, the short-term disadvantage of the fixed exchange rate in the Slovak economy was compensated for later on when the benefits of monetary union materialized. After 2010, rapid accumulation of entrepreneurial net worth was restored in Slovakia while in the Czech economy there was a period of stagnation. In this period the growth of net worth in Slovakia clearly surpassed even the development in the euro area. The decline of entrepreneurial net worth in 2012 and 2013 can be attributed to the protracted course of the European sovereign debt crisis and the crisis of the Eurozone. Even though the Czech economy was not hit by these events directly, the growth of net worth was restored there only after the exchange rate interventions of the Czech National Bank in the last quarter of 2013. In Hungary the situation during the crisis was further complicated by the currency crisis caused by the extraordinarily high share of foreign currency denominated debt. In the remaining Visegrád economies, the situation slightly improved in 2011, while in Hungary a currency depreciation in the latter half of that year precipitated the process of deleveraging and the credit conditions remained tight. In 2012, the situation in Hungary worsened further due to policy uncertainty and surtaxes imposed on the financial sector. During 2013 and 2014 the situation in Hungary seems to have improved significantly. According to the real data, there was an improvement in private investment. However, the housing sector continues to fall and much investment is made by the government and financed from EU funds.

Apart from the Great Recession, the model also captured the turbulence in the Hungarian economy in 2003, when large macroeconomic imbalances caused by expansionary fiscal policy became evident and an open conflict erupted between the government and the central bank on the policy mix. A period of exchange rate turbulence, major policy interest rate hikes and large scale capital outflow ensued. An increase of the external finance premium in the Polish economy in 2001 corresponds to a period of economic difficulties in the aftermath of the 1998 Russian crisis. After a period of loose monetary policy, monetary policy eventually tightened in order to reduce the macroeconomic imbalances incurred, which led to a plunge in investment in 2001.

Figure 5.17: Selected filtered variables



Source: Author.

Note: Per cent deviations are depicted, dashed line - CZ, vertical line - 2009Q1.

Overall, the main tendencies in the development of the unobserved endogenous variables of the financial market are identified quite similarly across the examined economies. In the period of the Great Recession, the development of depicted variables in the Czech and Polish economies was very similar. In the case of Slovak economy and the economy of the euro are, the increase of the external finance premia was markedly stronger than in the Czech economy. Therefore, the stress in the financial sector was arguably more severe in these economies. The case of the Hungarian economy is quite specific because the increase of the external finance premium was much more persistent than in the remaining economies. Also, the quick and substantial improvement of the situation in the Hungarian economy, as indicated by the development of the financial sector variables, is unparalleled.

5.7 Filtered time-varying parameters

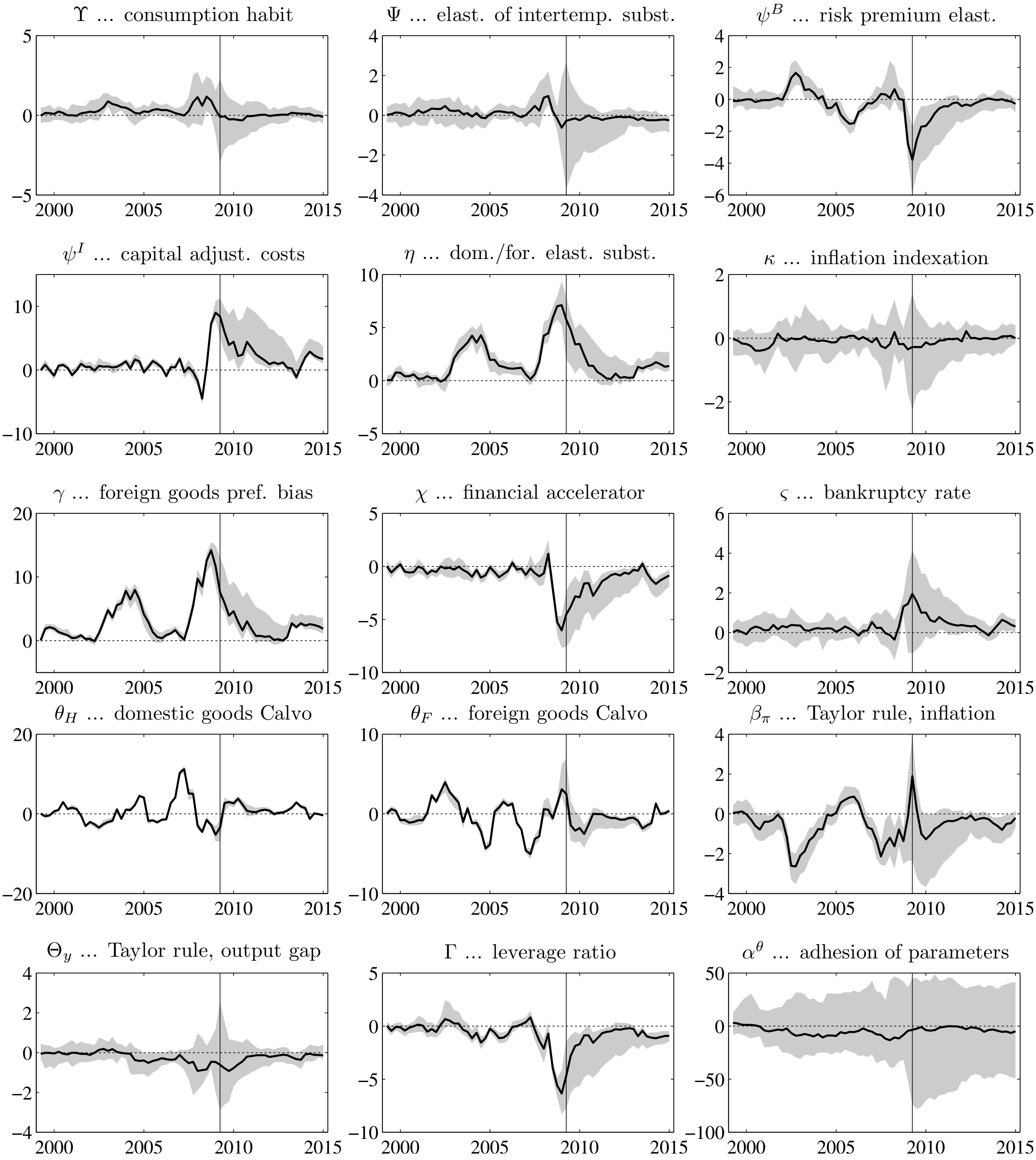
In this section, the development of the filtered trajectories of the structural time-varying model parameters as identified by the nonlinear particle filter is presented and discussed. Figures 5.18 through 5.22 depict deviations of the time-varying parameters from their respective initial values in per cent. The initial values correspond to the fixed estimates obtained by the Metropolis-Hastings estimation. The trajectories of the time-varying parameters in the absolute terms and 95 % HPDI bounds are included in the Appendix C, section C.7. These graphs can be used to asses the statistical significance of the deviations of the time-varying parameters from their respective initial values.

Figure 5.18 shows the development of the time-varying parameters in the Czech economy. Most of the financial sector parameters showed significant deviations from the initial values in the period of 2008–2010. In the period of economic boom of 2008, the entrepreneurial net worth increased, which led to lower interest rate spreads. According to the trajectory of external finance premium elasticity χ, the interest rate spreads also became less sensitive to the variations in the leverage ratio. Improving situation of the entrepreneurs is also reflected in the trajectory of the steady-state leverage ratio Γ that decreased at that time, which means that the firms were becoming less dependent on the external financing. However, as the capital stock deviated above its steady state it became increasingly difficult to find suitable investment opportunities and capital adjustment costs Ψ_I increased. Steady-state bankruptcy rate showed only a slight increase in the second half of 2008. The onset of the crisis in 2009 meant a correction and the values of the financial sector parameters slowly returned to the vicinity of their initial values.

Development of foreign goods preference bias γ and elasticity of substitution between domestic and foreign goods η can be related to the changing openness of the Czech economy and the development of international trade. Foreign goods preference increased during 2007–2008 and declined after 2008 with the onset of worldwide economic difficulties and downturn in international trade.

The filtered trajectories of the Calvo parameters show declining rigidity in the prices of the domestic goods θ_H during 2007 and 2008. Demand as well as wage growth was strong in this period of economic boom. On the other hand, the rigidity of the prices of imported goods θ_F is estimated to have increased, probably due to the appreciation of the real exchange rate easing supply-side pressures. During 2009 the situation reversed as foreign demand faltered, domestic supply-side pressures eased and the real exchange rate depreciated. After 2010, the Calvo parameters returned to the vicinity of their respective initial values. In the Czech economy, the domestic Calvo parameter increased due to weak demand during the 2012-2013 recession, which intensified disinflationary pressures. After the Czech National Bank's exchange rate intervention in the last quarter of 2013 put the prices of importers under pressure, the Calvo parameter of the importing firms increased above its initial value. Since the domestic demand in the Czech economy was relatively weak, importers were willing to absorb part of the cost increase, thus increasing price stickiness. The rising prices of imported goods (although limited) made room for the domestic producers of substitute goods to slightly increase their prices as well, which is reflected in the decline of the domestic Calvo parameter. This development is in line with the expected impact of the exchange rate intervention as communicated by the Czech National Bank, and would suggest that the intervention was successful in its main goal of avoiding deflation in the Czech economy.

Figure 5.18: Filtered time-varying parameters (deviations in per cent), CZ



Source: Author.

Note: Per cent deviations from initial values are depicted, vertical line - 2009Q1.

The substantial decline of the debt-elastic risk premium ψ^B in the Czech economy during the 2008-2009 crisis suggests that the Czech koruna was still perceived to be a regional safe haven, but the government's announced austerity measures probably played an important role as well. Therefore, the Czech currency did not depreciate as much as the local currencies in the remaining Visegrád economies despite the negative economic outlook.

Parameters of the Taylor interest rule as well as remaining structural parameters, including the consumption habit of households Υ, elasticity of intertemporal substitution Ψ, and inflation indexation of prices κ, are relatively stable and can be considered time-invariant (deep).

Figure 5.19 contains the filtered trajectories of selected time-varying parameters in the Czech and Slovak economies. The development of the financial accelerator parameter χ (the elasticity of the external finance premium with respect to the leverage ratio) in the Czech economy would suggest that the reaction of commercial banks to the deteriorating leverage ratio in 2008 was somewhat subdued. The commercial interest rates were not raised too sharply, perhaps due to initial optimism about the length and spread of the financial crisis. However, after the first quarter of 2009, the impact of the financial crisis on the real economy was becoming evident and the sensitivity of the external finance premium began to rise again. In the case of Slovakia the decline of sensitivity was not as considerable and the return to initial values much quicker. However, a second decline of the financial accelerator comparable in size to the decline in the Czech economy can be distinguished during 2009 and early 2010, when the net worth of Slovak entrepreneurs deteriorated significantly.

The filtered trajectory of the steady state leverage ratio parameter Γ shows that the dependency of firms on external financing in the period of economic boom of 2007-2008 decreased both in the Czech and Slovak economies. However, this development was reversed after the last quarter of 2008 due to worsening macroeconomic conditions. The more severe impact of the economic crisis on the Slovak economy in comparison with the Czech economy is reflected in the larger increase of the share of external funds held by the domestic firms.

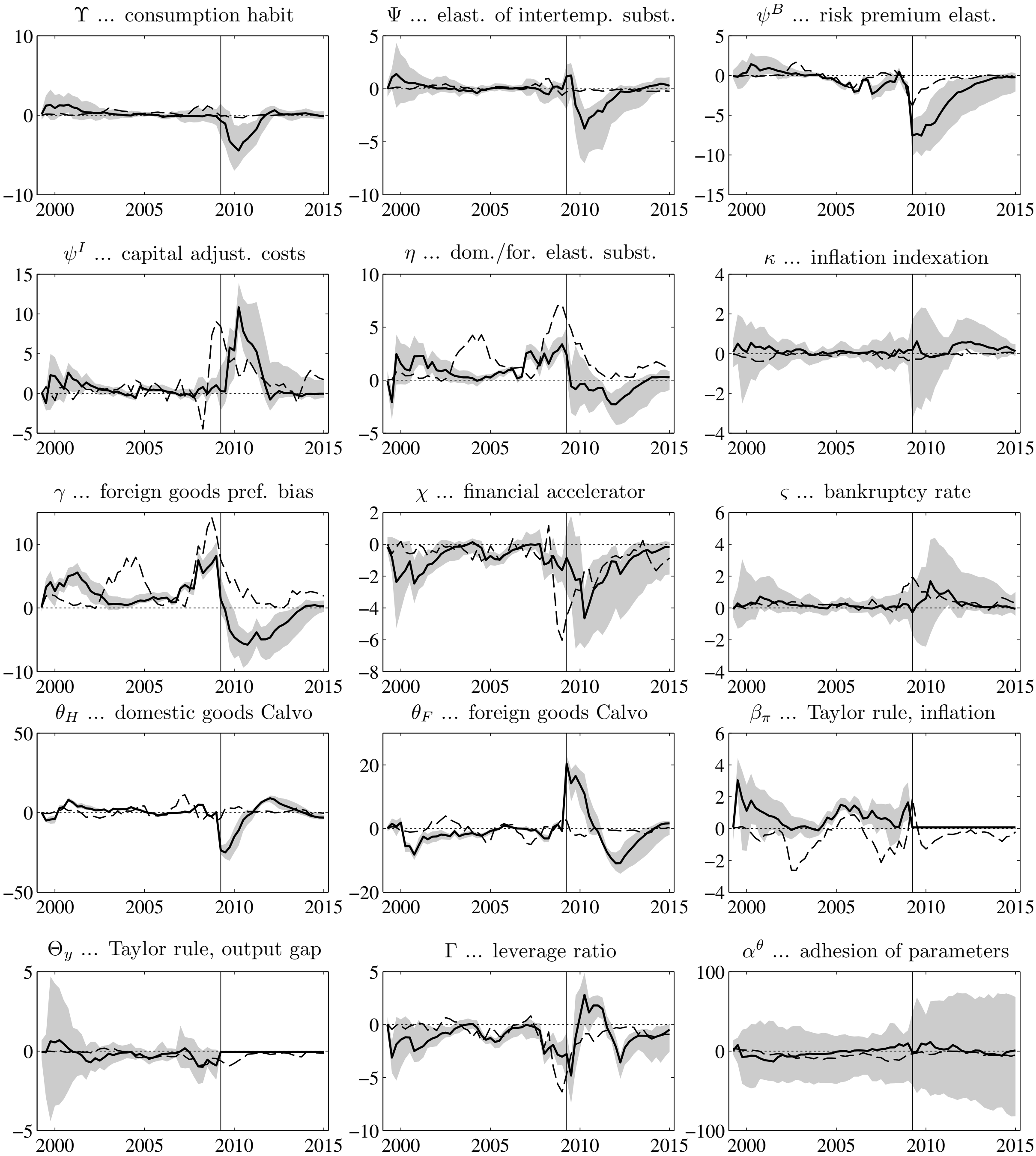
The increasing capital adjustment costs parameter Ψ^I in the Czech economy during 2008 could be explained by the increasing difficulty of finding viable investment opportunities in an arguably overheated economy, and would indicate that an increasing share of investment was being made inefficiently. In the Slovak economy similar developments occurred in the second half of 2009, when the European debt crisis loomed and the inflow of foreign direct investment was stalling.

Overall, the filtered trajectories of the financial frictions parameters suggest that the situation in the financial sector of the Czech economy was changing as early as 2008, while in Slovakia prospects were still quite positive in light of the anticipated euro adoption, and the situation became turbulent only after the actual impact of the economic crisis in 2009 and subsequently due to the European debt crisis in 2010.

The parameters of elasticity between domestic and foreign goods η and foreign goods preference bias γ (the share of foreign goods in consumption) tell a similar story. As the volume of international trade increased in the pre-crisis period, the share of imported goods together with the sensitivity of domestic economic agents to the price differential between domestic and foreign goods also increased. Over the course of the crisis the situation reversed. The current development of these parameters suggests that the situation in the Slovak economy is roughly stable while in the Czech economy the increase of these parameters could be related to recovering consumer confidence.

The filtered trajectories of the Taylor rule parameters are more or less stable. Given the strict nature of the inflation targeting regime in the Czech economy, the stability of the weight of the inflation gap β_π should be no surprise. Also, the monetary policy of Slovakia, as a euro zone candidate, would be expected to follow the development of inflation closely (in order to meet the requirements for euro adoption), while the output gap would not necessarily be a priority. The mostly negative deviations of the output gap weight Θ_y from its initial value would indeed suggest that the Czech and Slovak central banks do not place much importance on the output gap in their decision making.

Figure 5.19: Filtered time-varying parameters (deviations in per cent), SK



Source: Author.
Note: Per cent deviations from initial values are depicted, solid line - SK, dashed line - CZ, vertical line - 2009Q1.

Finally, the Calvo parameters, which capture the price stickiness of domestic and foreign goods retailers, show distinct deviations from their initial values as well. The most significant deviation of the time-varying parameters is identified in the Slovak economy during the transition period after the euro changeover. The price rigidity of domestic retail firms θ_H is estimated to have almost halved its initial value. At the same time the price rigidity of importing retail firms θ_F increased significantly. Obviously, the currency changeover represented an opportunity for domestic firms to round up and adjust the prices of their products, and at the same time made it more important to monitor the pricing strategy of competitors. Therefore, in the transition period before new prices are settled, lower price rigidity should be expected. The increased price rigidity of importers can be explained by the favourable setting of the conversion rate of the Slovak koruna and disinflationary tendencies in the foreign economy that allowed importers to remain competitive with prices relatively unchanged.

Figure 5.20 contains the filtered trajectories of selected time-varying parameters in the Czech and Polish economies. Apart from the period of 2000-2003, when the Polish economy slowly recovered from the aftermath of the 1998 Russian crisis, the filtered trajectories of the Polish economy show much lower volatility in comparison to the Czech economy. This result can be partially explained by the relatively large size of the Polish economy, which is 2.5 times as large as the Czech economy, and also by its lower openness to international trade , which makes it more resilient to foreign crises.

The development of the financial accelerator parameter χ (the elasticity of the external finance premium with respect to the leverage ratio) in the Czech economy suggests that the reaction of the commercial banks to the deteriorating leverage ratio in 2008 was subdued. However, after the first quarter of 2009, the impact of the financial crisis on the real economy was becoming evident and the sensitivity of the external finance premium began to rise again. In the case of Poland the decline of sensitivity was slightly delayed and not as substantial as in the Czech economy.

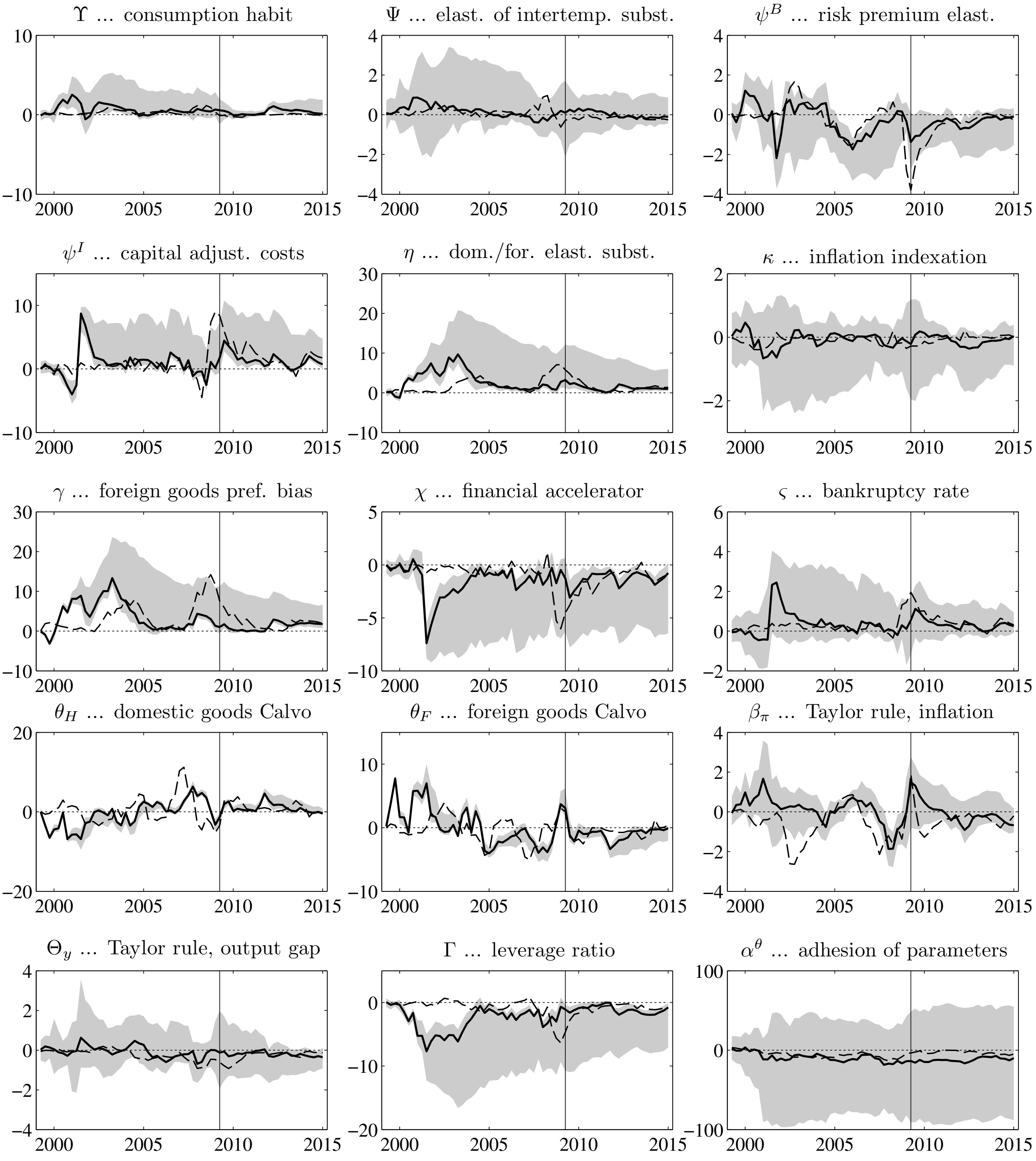
The trajectory of the steady-state leverage ratio Γ in the Czech economy captures the improving conditions in the period of economic boom 2007-2008. The situation, however, worsened quickly during the 2008-2009 crisis. In Poland, the development of this parameter was qualitatively similar, but the magnitude of the deviations from the initial value was much smaller. However, large deviations of this parameter can be distinguished in 2002 and 2003. The low leverage ratio in this period was probably one of the consequences of the Russian crisis, and its subsequent increase should be perceived as a positive development enabled by decreased uncertainty in the Polish economy.

Capital adjustment costs Ψ^I exhibit an increase during 2008 and 2009 in the Czech and Polish economies suggesting that clear investment opportunities were becoming scarce and investment efficiency was declining. Again such deviations are much larger in the Czech economy.

The trajectories of elasticity between domestic and foreign goods η and foreign goods share in consumption γ have the potential to partially explain the differences between the effects of the Great Recession in the two economies. Both these parameters increased significantly in the pre-crisis period in the Czech economy, thus boosting the volume of international trade together with the dependency of the Czech economy on the external environment. The negative effects of this development materialized in late 2008 and early 2009. By comparison, the development of import share γ in the Polish economy was much steadier during the Great Recession. However, our results suggest that the Polish economy underwent structural changes of a similar order of magnitude during the 2000-2003 crisis. After a successful restructuring of the industrial sector of the economy and reorienting on new export markets, the Polish economy lowered its dependence on the external environment.

The substantial decline of the debt-elastic risk premium Ψ^B in the Czech economy during the 2008-2009 crisis suggests that the Czech koruna was still perceived to be a regional safe haven, as it reacted to a worsening net foreing assets position during the crisis less then proportionately. In Poland, the decline of the debt-elastic risk premium was only marginal and the exchange rate depreciation was much stronger. The filtered trajectories of the Calvo parameters show a similar development in the Czech and Polish economies during the crisis.

Figure 5.20: Filtered time-varying parameters (deviations in per cent), PL



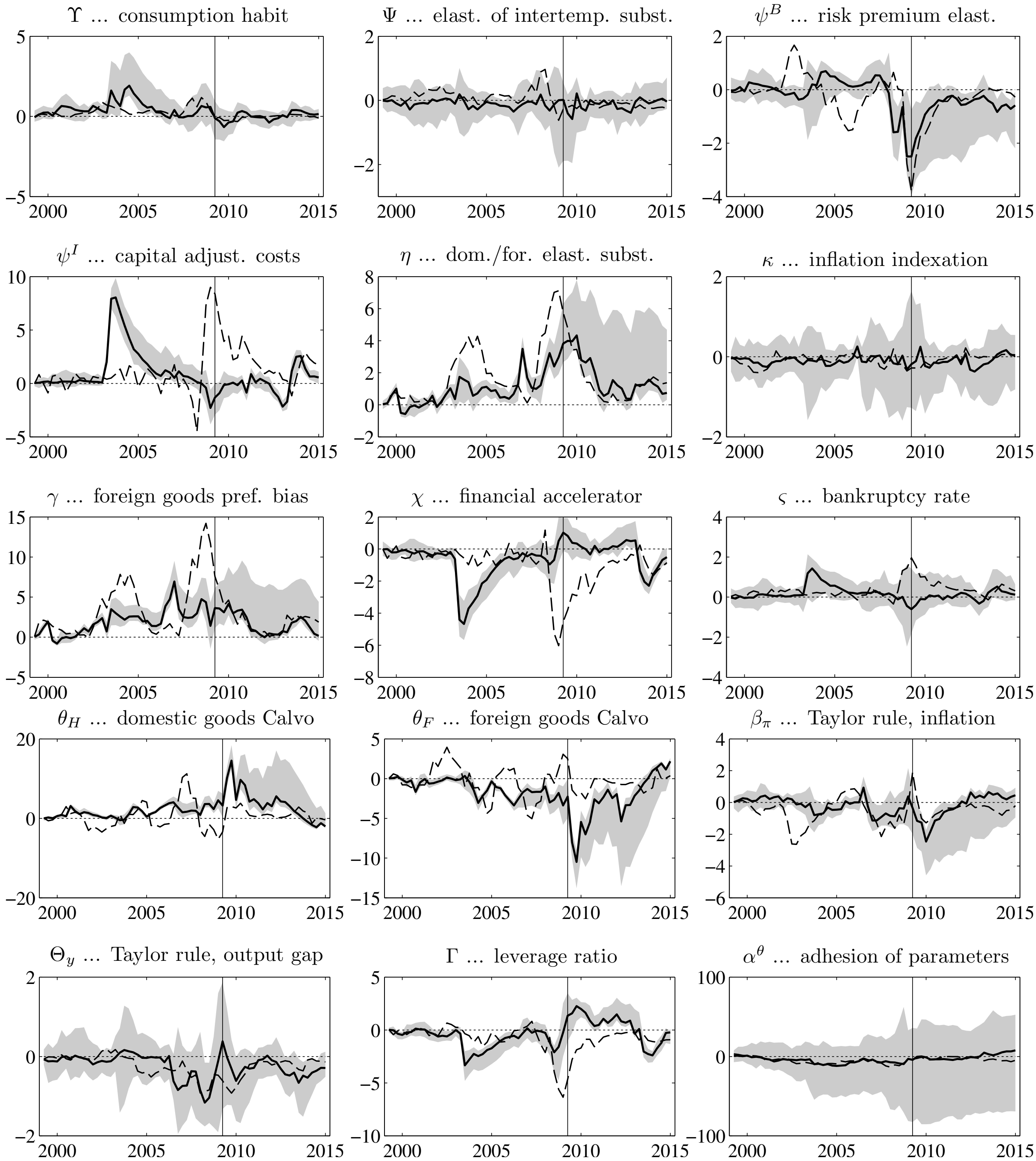
Source: Author.

Note: Per cent deviations from initial values are depicted, solid line - PL, dashed line - CZ, vertical line - 2009Q1.

A comparison of the development of selected time-varying parameters in the Czech and Hungarian economy is depicted in Figure 5.21. The development of financial accelerator χ was strongly influenced by the aforementioned Hungarian currency crisis in 2003. Before the Great Recession, this parameter increased slightly, it remained stable during the crisis and began to decline only recently in 2014. Similarly, the steady-state leverage ratio Γ

declined during the 2003 crisis in Hungary. Unlike in the Czech or Polish economies, the leverage ratio increased during the Great Recession, probably due to currency depreciation and the large share of foreign currency denominated debt. This development amplified the increase of the interest rate spread and further worsened the availability of debt financing in Hungary. The parameter of capital adjustment costs Ψ^I increased substantially during the 2003 crisis but remained mostly stable during the Great Recession.

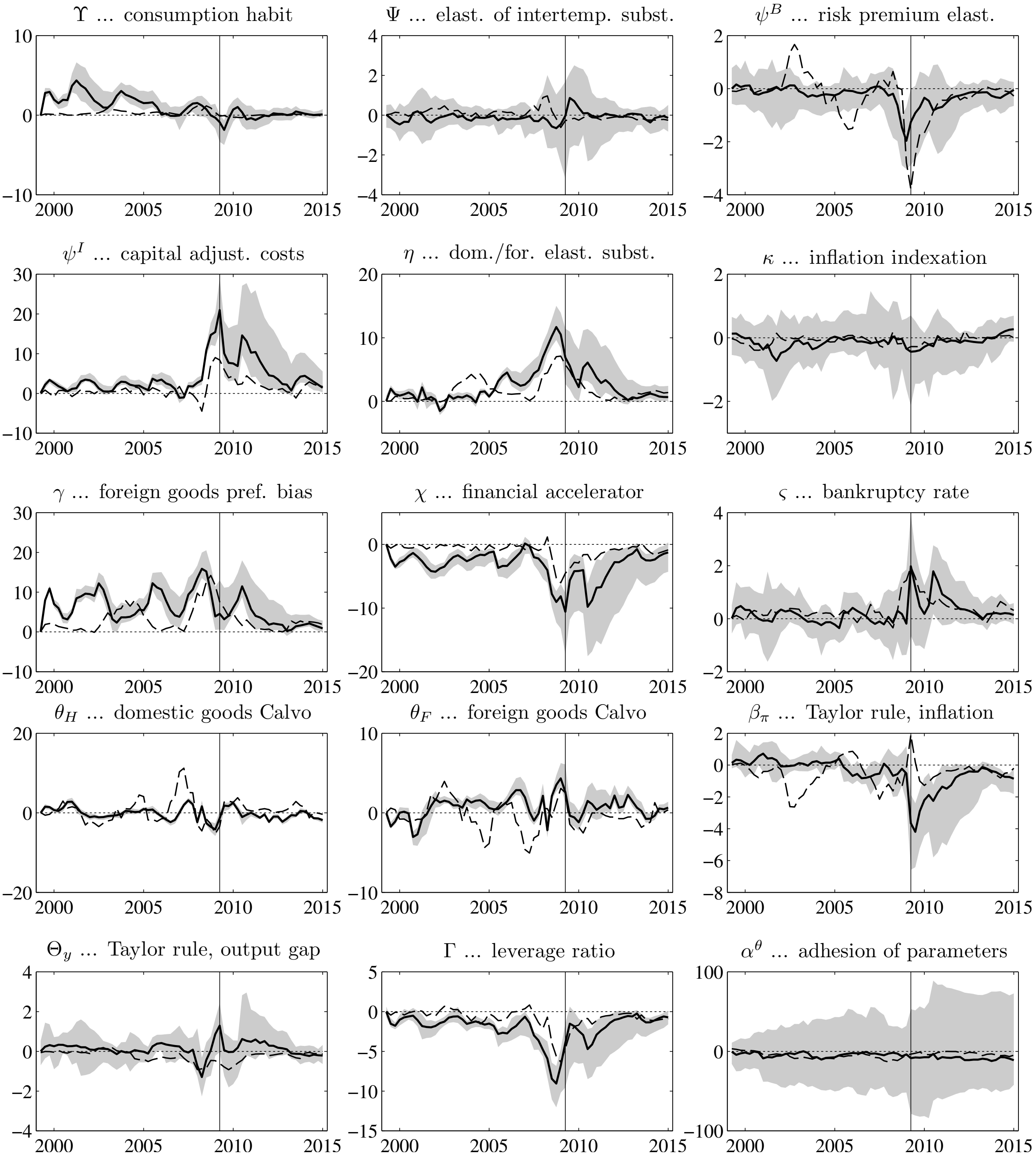
Figure 5.21: Filtered time-varying parameters (deviations in per cent), HU



Source: Author.
Note: Per cent deviations from initial values are depicted, solid line - HU, dashed line - CZ, vertical line - 2009Q1.

The elasticity between domestic and foreign goods η and foreign goods share in consumption γ in Hungary increased during 2006-2008 period, but the magnitude of the deviations from initial values was subdued in comparison to the Czech economy, probably because of the fiscal consolidation in 2007. These two parameters returned to their initial values during 2010.

Figure 5.22: Filtered time-varying parameters (deviations in per cent), EA



Source: Author.

Note: Per cent deviations from initial values are depicted, solid line - EA, dashed line - CZ, vertical line - 2009Q1.

The debt-elastic risk premium Ψ^B declined in the Hungarian economy in 2008 and 2009 due to fiscal consolidation and austerity measures, but the decline was not as considerable as in the Czech economy.

The filtered trajectories of the Calvo parameters show a rapid increase in the rigidity of prices of domestic goods θ_H during 2009. Domestic as well as foreign demand faltered and domestic supply-side pressures eased. Domestic retailers had to lower their profit margins and put price growth on hold. The rigidity of the prices of imported goods θ_F is estimated to have decreased during the crisis. Currency depreciation together with falling demand led to a complicated situation for importers, who had to react swiftly to the price adjustments of competitors. During 2010, the Calvo parameters returned to the vicinity of their respective initial values.

The downward deviation of the inflation weight in the Taylor rule β_π in 2009 suggests that the monetary policy reaction should have been more radical in Czech and Hungarian economies. Interest rates probably should have been lowered faster in order to counter the growing external finance premium.

The development of selected time-varying parameters in the Czech economy and the economy of the euro area is depicted in Figure 5.22. The deviations of the financial sector parameters in the euro area are estimated to be mostly in the same direction but with much larger amplitudes than in the Czech economy. The results correspond to the more immediate impact of the financial crisis on western European countries compared with relatively sheltered economies in Central Europe. The destabilizing impact of the European debt crisis is noticeable in the euro area in early 2010. Since mid-2010 the situation in the financial market in the euro area seems to have been gradually stabilizing.

During the Great Recession the elasticity of substitution between foreign and domestic goods η and the foreign goods preference bias γ declined, together with the volume of international trade. After a short-lived correction, these two parameters began to decline again in 2010 due to the sovereign debt crisis in the euro area. Recent estimates of these parameters indicate stabilization in this area as well.

The filtered trajectories of the Calvo parameters show roughly similar development in the Czech economy and the economy of the euro area during the crisis. The debt-elastic risk premium Ψ^B declined in the economy of the euro area in 2008 and 2009 as well as in the Czech economy, but the decline was not as substantial.

The downward deviation of the inflation weight in the Taylor rule β_π in 2009 in the euro area hints at the relatively weak reaction of the ECB to the impact of the financial crisis. This development was probably caused by underestimating the effects of the U.S. subprime mortgage crisis on European countries. In the Czech economy, the effects of the financial crisis were probably underestimated at first as well, since the inflation weight also declined below its initial value during 2009.

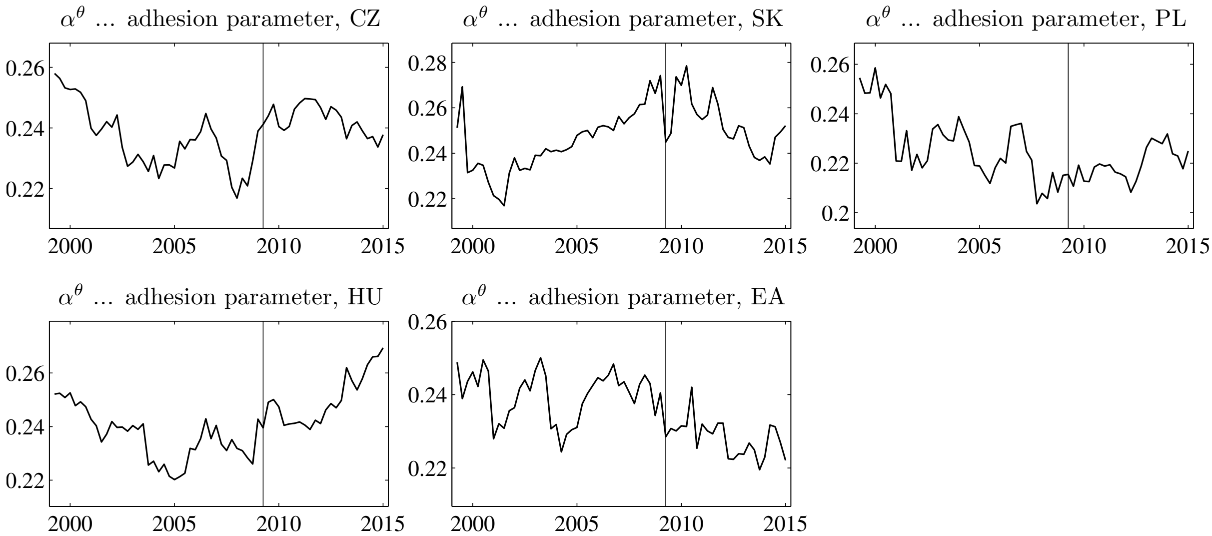
According to the graphs in the section C.7 in the Appendix C, most of the deviations of the time-varying parameters from their initial values cannot be considered statistically significant at the level of significance of 5 %. Only the deviations of the Calvo parameters and the steady state leverage ratio Γ can be considered statistically significant in all the economies (while in the case of the Hungarian economy the level of significance would be closer to 10 %). The deviations of the elasticity of substitution between domestic and foregin goods η in Poland and in the euro area can be also considered statistically significant. In the euro area, even the deviations of the foreign goods preference bias γ and capital adjustment costs ψ^I are on the verge of statistical significance.

Figure 5.23 compares the trajectories of the time-varying adhesion parameter α^θ in all the examined economies. The adhesion parameter reflects the general tendency of the remaining time-varying parameters in a given economy to return to their initial values. The filtered values fluctuate around the initial value of 0.25, between a minimum of 0.22 and maximum of 0.28.

We can distinguish a period of lower adhesion in all the economies with the exception of Slovakia during 2004-2005 when the Central European economies joined the European

Union. In the Czech and Polish economies, there is a distinguishable decline of adhesion in the period of economic boom between 2007 and 2008. In the Slovak economy, there is a distinct growth of adhesion between 2001 and 2008 with a temporary fall during the early phase of the crisis. In the Polish economy, lower adhesion can be found also in the period between 2002 and 2003. In the Hungarian economy, the adhesion increased during the crisis. In the euro area the adhesion culminated in 2007 and it declined slightly during the crisis. Since the Great Recession, the adhesion has remained relatively stable in the Czech and Polish economies, while in Hungary it increased progressively and in the Slovak economy and the economy of the euro area the adhesion is generally declining.

Figure 5.23: Filtered time-varying adhesion parameter comparison



Source: Author.
Note: Vertical line - 2009Q1.

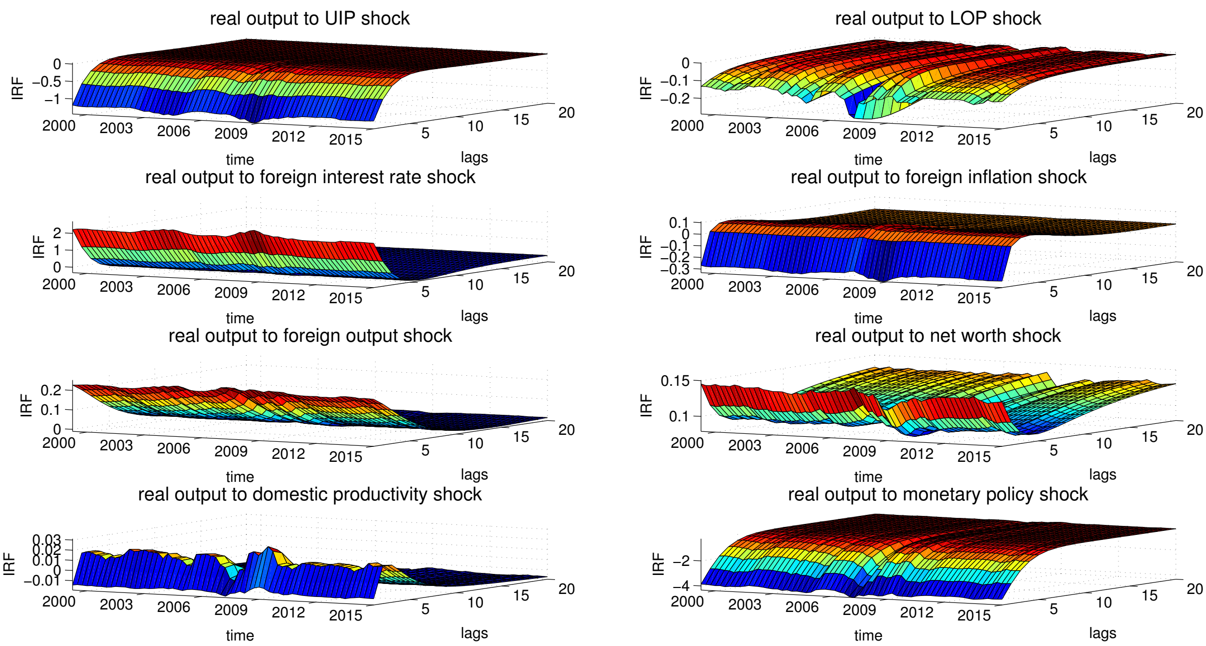
The periods of lower adhesion often correspond to times when the economies underwent important structural changes. In general, the structural parameters deviated further away from their initial values in these periods. As many structural parameters reached exceptional values, the tendency of the economy to return to its initial structure strengthened and the adhesion subsequently increased. Therefore, the development of the adhesion parameter can be also interpreted in a following way. A decline of the adhesion parameter indicates a growing structural instability while an increase shows corresponds to a general increase of the firmness of the economic structure.

5.8 Time-varying impulse responses

In this section, the impact of the time-varying economic structure on the behaviour of given economy is investigated. We focus on the time-varying impulse response functions of the real output, because it is ultimately the most interesting economic variable that is discussed in professional circles as well as in the media and in public. In the figures included in this section, only the impulse responses of the Czech economy are depicted. The results for the remaining Visegrád economies and the economy of the euro area are included in the Appendix C, section C.8.

Figure 5.24 shows the impulse responses of the real output in the Czech economy with time-varying structure to the shock innovations of a constant magnitude. Impulse responses to 1 % shock innovations are depicted. This graph allows us to see, when the sensitivity of the Czech economy to a particular exogenous shock increased or decreased due to underlying changes of the structural parameters.

Figure 5.24: Time-varying IRFs of real output, constant shocks, CZ

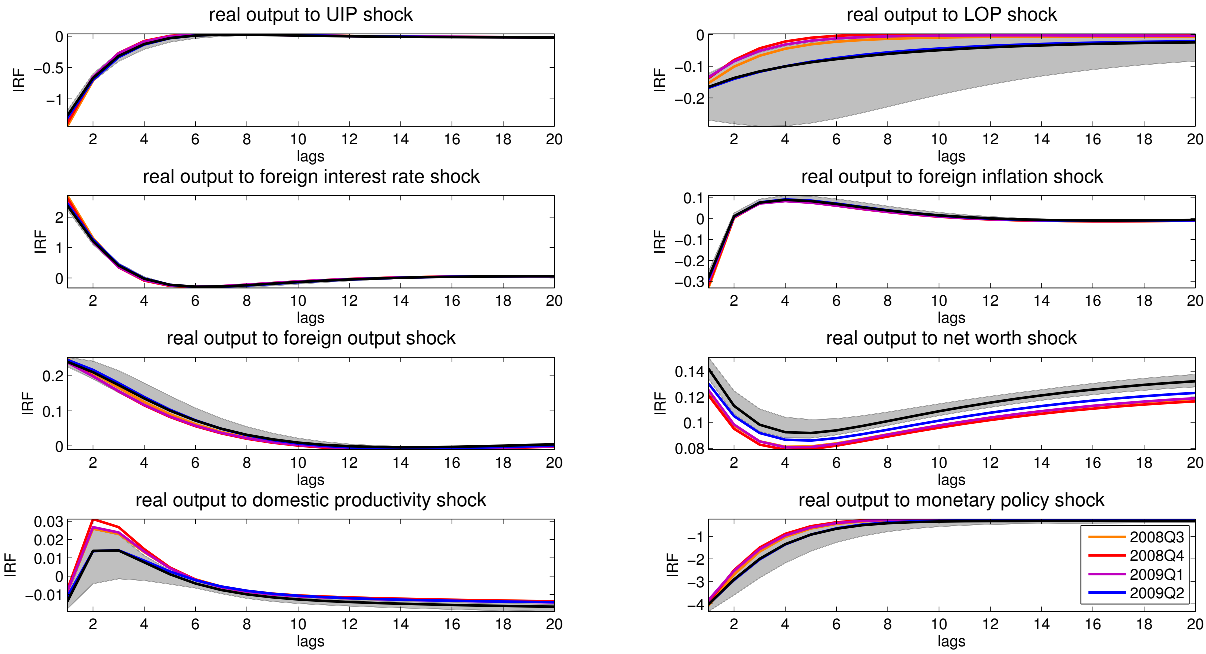


Source: Author.
Note: Percentage deviations caused by 1% shocks are depicted.

We can see distinct changes in the impulse responses around the time of the pre-crisis boom and subsequent impact of the economic crisis between 2007-2009. While the impulse responses to the UIP shock, foreign shocks and monetary policy shock remain relatively stable, increased sensitivity to the law of one price shock and the net worth shock is apparent in the pre-crisis period. Sensitivity to the productivity shock was decreased in the pre-crisis period. During the crisis the sensitivity to the law of one price shock and the net worth shocks decreased and afterwards returned to vicinity of the long-run average. Sensitivity to the productivity shock increased during 2008 and after 2009 it returned to the long-run average. The obtained results imply that in the upbeat pre-crisis period of economic boom, the changes in the behaviour of the economic agents, as captured by the filtered time-varying structural parameters, amplified the mostly positive innovations of the law of one price shock and the net worth shock. Inversely, during the crisis, the structural changes limited the impact of the negative innovations in these shocks.

In Figure 5.25 the individual impulse responses of the real output to the exogenous shocks between 2008Q3 and 2009Q2 are depicted in order to see the changes in the behaviour during the crisis more clearly. Size of the exogenous shock innovations is fixed to 1 % so only the economic structure changes. The graphs also display a shaded band, where the impulse responses occurred in the pre-crisis period, and the pre-crisis mean. We can confirm the stability of the responses to the UIP shock, foreign interest rate shock and foreign inflation shock. The impulse responses to the real output shock and the monetary policy shock are also relatively stable and durign the crisis they kept close to the pre-crisis mean. On the other hand, the amplitude of the impulse responses to the law of one price shock and the net worth shock were somewhat smaller during 2008Q3-2009Q1 and they returned to the pre-crisis mean in 2009Q2. The amplitude of the productivity shock was on the contrary higher in the 2008Q3-2009Q1 period and it declined towards the pre-crisis mean in 2009Q2.

Figure 5.25: Time-varying IRFs of real output, constant shocks, projection, CZ



Source: Author.

Note: Percentage deviations caused by 1% shocks are depicted, shaded area - pre-crisis period (2003Q3-2008Q2), black line - pre-crisis mean.

In case of the Slovak economy, the comparisons are complicated by the deep structural change caused by entering the European monetary union. The impulse responses since 2009Q2 are therefore quite dissimilar to the pre-crisis period. Nevertheless, we can see that the structural changes in the Slovak economy influenced mainly its sensitivity to the law of one price shock innovations in the pre-crisis period.

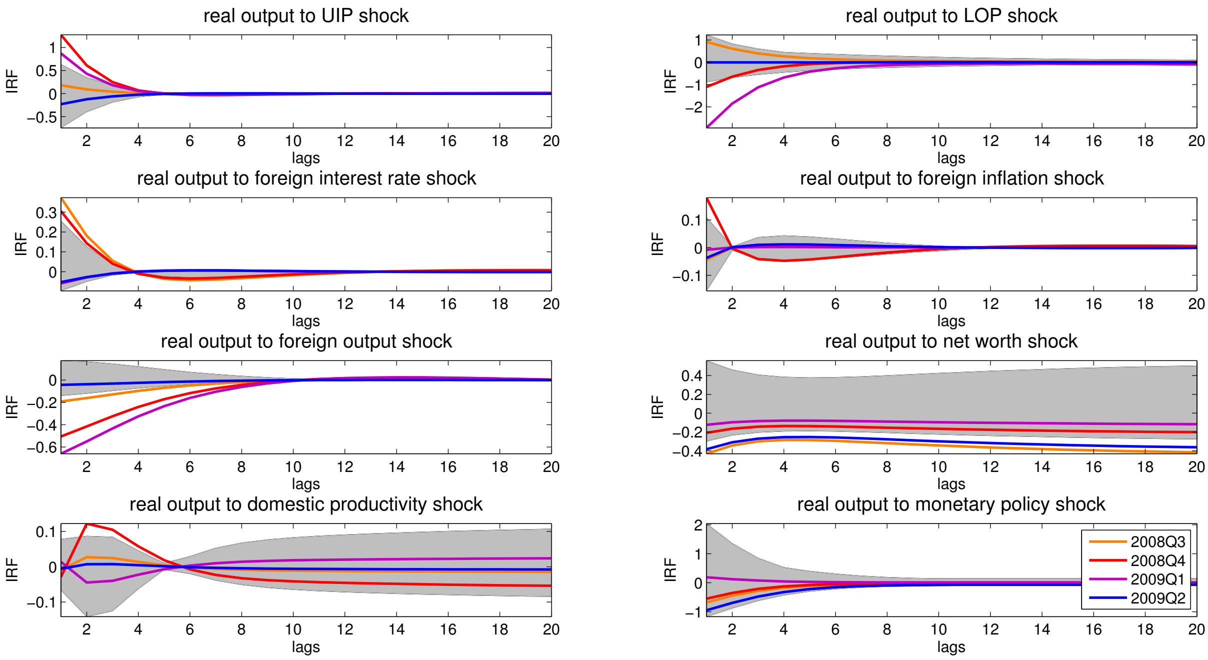
In the Polish economy, we can see similar results as in the Czech economy. The sensitivity to the LOP shock was influenced the most by the structural changes in the pre-crisis period. Shortly before the crisis, the sensitivity to this shock was decreased and after 2009Q1 it returned to the long-run average. In case of the net worth shock, the sensitivity was very slightly increased before the crisis as well. In case of the productivity shock, the sensitivity of the real output to this shock was slightly elevated before the crisis.

The sensitivity of the Hungarian real output to the exogenous shocks changed later during the Great Recession than in the economies discussed above. Changes in the impulse responses of the real output to 1 % shock innovations are identified in 2009Q2. Most notably it is the increase in the sensitivity to the LOP shock, but to a small extent sensitivity to other shocks also changed in this period.

Changes in the sensitivity of the euro area economy real output during the interval 2008Q3-2009Q2 are comparable to the Czech economy.

Unlike previous two figures, Figure 5.26 depicts the impulse responses of the real output in the Czech economy with time-varying structure to the historical shock innovations as identified by the nonlinear particle filter. The graphs therefore capture both, the changes in the underlying economic structure and the varying size of the shock innovations. The graphs of this type allow us to assess the exceptionality of the period of the Great Recession. We can see that the responses to the exogenous shock innovations in interval 2008Q3-2009Q2 were often quite exceptional and far beyond the region common in the pre-crisis period. Most notably, the large negative innovations in the foreign demand captured by the foreign output shock in 2008Q4 and 2009Q1, the negative law of one price shock innovations in 2009Q1 and the negative UIP shock innovations in 2008Q4 and 2009Q1 show the unprecedented size of the disturbances experienced by the Czech economy during the crisis.

Figure 5.26: Time-varying IRFs of real output, historical shocks, CZ



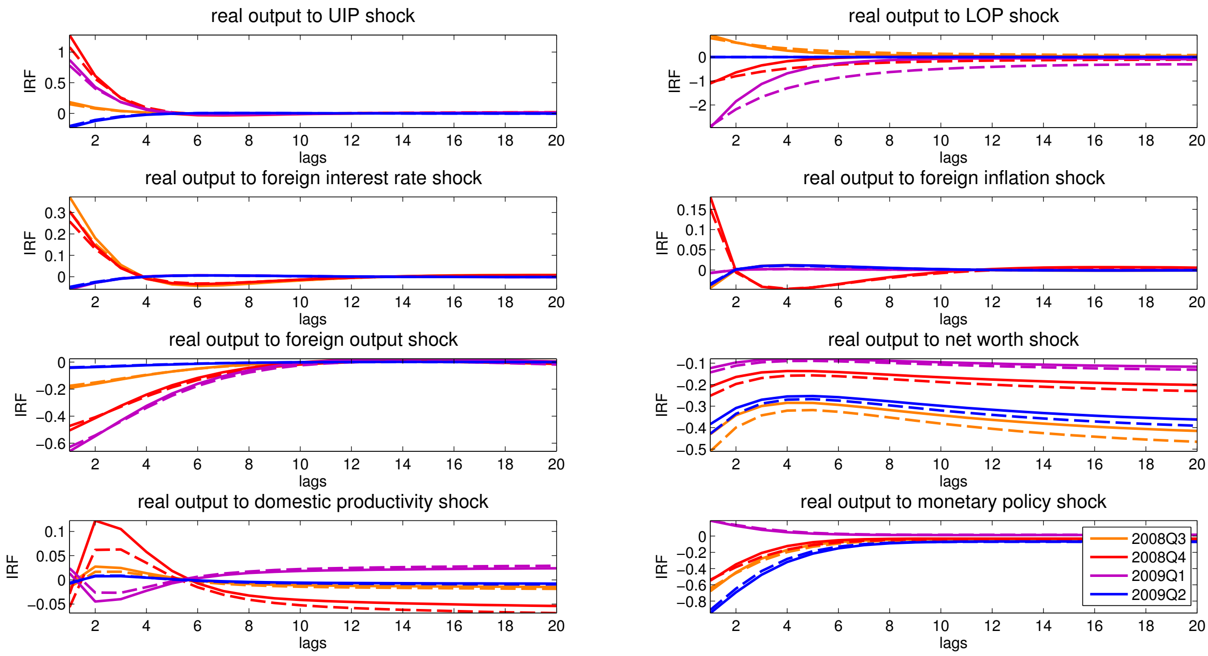
Source: Author.
Note: Percentage deviations caused by 1% shocks are depicted, shaded area - pre-crisis period (2003Q3-2008Q2).

Figure 5.27 compares the impulse responses of the real output to the historical shocks in the Czech economy with time-varying structure identified by the nonlinear particle filter and in the Czech economy with the time-invariant baseline structure identified by the Random Walk Metropolis-Hastings algorithm. Using this type of graph, we can explicitly see the influence of the time-varying economic structure on the impulse responses of given economy in particular historical period. In the case of the Czech economy, we can see that the time-varying economic structure did not significantly alter the impulse responses to the UIP shock, foreign shocks or the monetary policy shock. Structural changes amplified the impulse responses to the productivity shock in 2008Q4 quite considerably. In case of the law of one price shock, the structural changes lead to a lower persistence of the impulse responses of the real output to this shock in 2008Q4 and 2009Q1. On the other hand, the structural changes dampened the impulse responses to the net worth shock in the period of 2008Q3-2009Q2.

In the Slovak economy, the exceptionality of the crisis period is apparent from the responses to the foreign output shock, productivity shock, net worth shock and to a smaller extent also law of one price shock innovations. In comparison to the baseline time-invariant model, the time-varying economic structure influenced the impulse responses especially after the accession to the eurozone, when it dampened the impulse responses to the UIP shock, LOP shock and foreign output shock while amplifying the response of the real output to the productivity shock.

In the Polish economy, extraordinary impulse responses of the real output to the foreign output shock, net worth shock, UIP and LOP shocks were identified during the crisis. The structural changes did not significantly influence the responses of the real output to the exogenous shock innovations during the crisis.

Figure 5.27: Time-varying IRFs of real output, historical shocks, comparison, CZ



Source: Author.
Note: Percentage deviations caused by 1% shocks are depicted, solid lines - time-varying structure, dashed lines - baseline structure.

In case of the Hungarian economy, impulse responses of the real output to the historical shocks that leave the pre-crisis band during 2008Q3-2009Q2 interval were identified in case of foreign output shock, LOP shock but also monetary policy shock. The positive innovation in the monetary policy shock in 2008Q4 that lead to a further decrease of the Hungarian real output is paralleled only by the Slovak economy. In case of the Slovak economy, the tightening of the monetary policy can be explained by the expected euro adoption and related efforts to contain the inflation in the pre-crisis period. In Hungary, the monetary policy tightening aimed to reduce relatively high inflation in the pre-crisis period and to defend the exchange rate of the domestic currency in an environment of high foreign currency denominated debt. The changing economic structure lead to decreased amplitude of the impulse responses of real output to the productivity shock, and at the same time more pronounced reaction to the foreign output shock and more persistent responses to the law of one price shock.

In the economy of the euro area, exceptional impulse responses of the real output can be identified during 2008Q3-2009Q2 in case of the net worth shock, foreign demand shock and LOP shock, but also monetary policy shock and to a smaller extent the UIP shock. The exceptionality of the real output response to the monetary policy shock is given by the relatively well-behaved inflation in the euro area in the pre-crisis period when it fluctuated closely around the inflation target. In the period of economic overheating and growing inflation pressures during 2008, the monetary policy authority had to act more decisively than before. Compared to the baseline model, the changes in the economic structure dampened the reaction of the real output to the net worth shock and to a lesser extent to the monetary policy shock and reduced the persistence of the LOP shock in the period 2008Q3-2009Q2. On the other hand the structural changes brought more distinct responses to the foreign output and foreign interest rate shocks and altered the reaction to the productivity shock as well.

Chapter 6

Sensitivity analysis

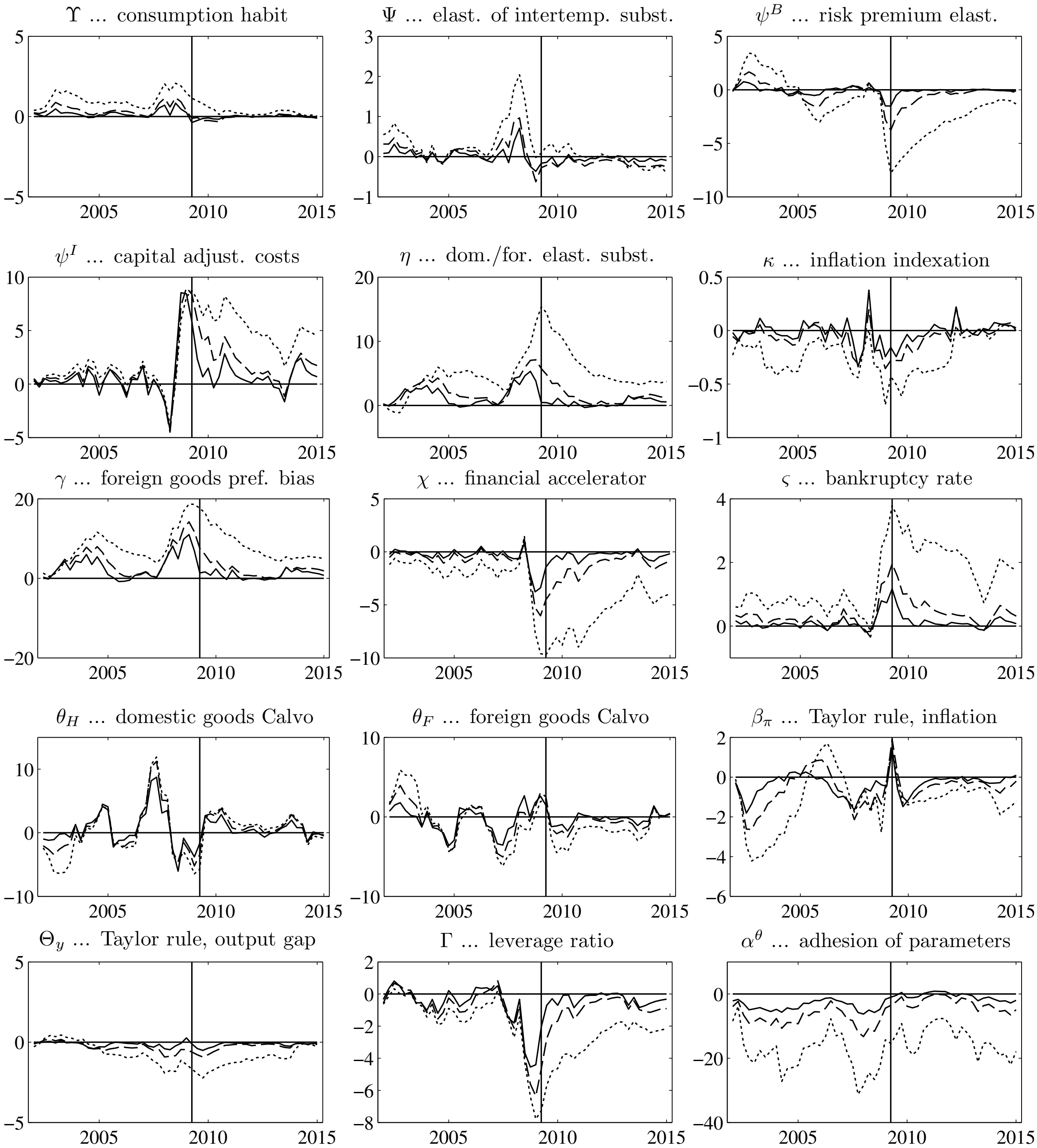
Since several arbitrary choices had to be made in order to set-up the nonlinear particle filter algorithm, a sensitivity exercise is performed in this section to assess the sensitivity of the obtained results. First, we had to calibrate the initial value of the time-varying adhesion parameter α_0^θ, which influences the tendency of the time-varying parameters to return to their respective initial values. The baseline value of this parameter was set to 0.25. In this section, we compare the results obtained with the calibration of 0.10, 0.25 and 0.50. Next, we selected which parameters should be considered time-varying and which should be time-invariant. At first, only the set of structural parameters presented in the graphs throughout the thesis were considered time-variiyng, next the shock AR(1) parameters and finally the foreign SVAR(1) block parameters were added. The common adhesion parameter was set to $\alpha^\theta = 0.25$ in this comparison. Finally, we compare the trajectories of the time-varying parameters obtained by the nonlinear particle filter to the recursive estimates obtained by the Random Walk Metropolis-Hastings algorithm. The recursive estimation represents an alternative method that enables us to track the changes in the underlying economic structure. Unlike the nonlinear particle filter, the recursive estimation estimates all the model parameters in every period including the shock parameters. Therefore, it is not possible to choose which parameters should or should not be considered time-varying. The recursive Random Walk Metropolis-Hastings algorithm was set to compute two chains of 100.000 samples in each period between 2004Q1-2014Q4. The calibration and setting of the priors is the same as in the estimation of the baseline model with time-invariant parameters presented in section 5.2. Once again, only the graphs containing the results of the Czech economy model are presented in this section. Graphs depicting the results of the sensitivity exercise for the remaining Visegrád economies and the economy of the euro area are included in the Appendix C, sections C.9 (adhesion calibration), C.10 (parameter selection) and C.11 (recursive estimation).

6.1 Calibration of the adhesion parameter

Comparison of the filtered trajectories of the time-varying structural parameters of the Czech economy depending on the calibration of the adhesion parameter α_0^θ is depicted in Figure 6.1. According to the presented results, nonlinear particle filter is a relatively robust tool for identification of unobserved trajectories of time-varying parameters in DSGE models. The filtered trajectories of structural parameters with different initial values of common adhesion parameter are very similar. The periods where given parameters increased and decreased are identified almost identically. The differences in maximum deviations from initial values are only minor between the two alternatives with $\alpha_0^\theta = 0.25$

and $\alpha_0^\theta = 0.5$. With $\alpha_0^\theta = 0.1$ the parameters deviate further from their initial values and especially during the Great Recession they stay away for a longer period of time. This is given by the fact that with $\alpha_0^\theta = 0.1$ the model definition of the time-varying parameters approaches a random walk.

Figure 6.1: NPF sensitivity to adhesion parameter calibration, CZ



Source: Author.

Note: Percentage deviations from initial values are depicted, solid line - $\alpha_0^\theta = 0.5$*, dashed line -* $\alpha_0^\theta = 0.25$*, dotted line -* $\alpha_0^\theta = 0.10$*, vertical line - 2009Q1.*

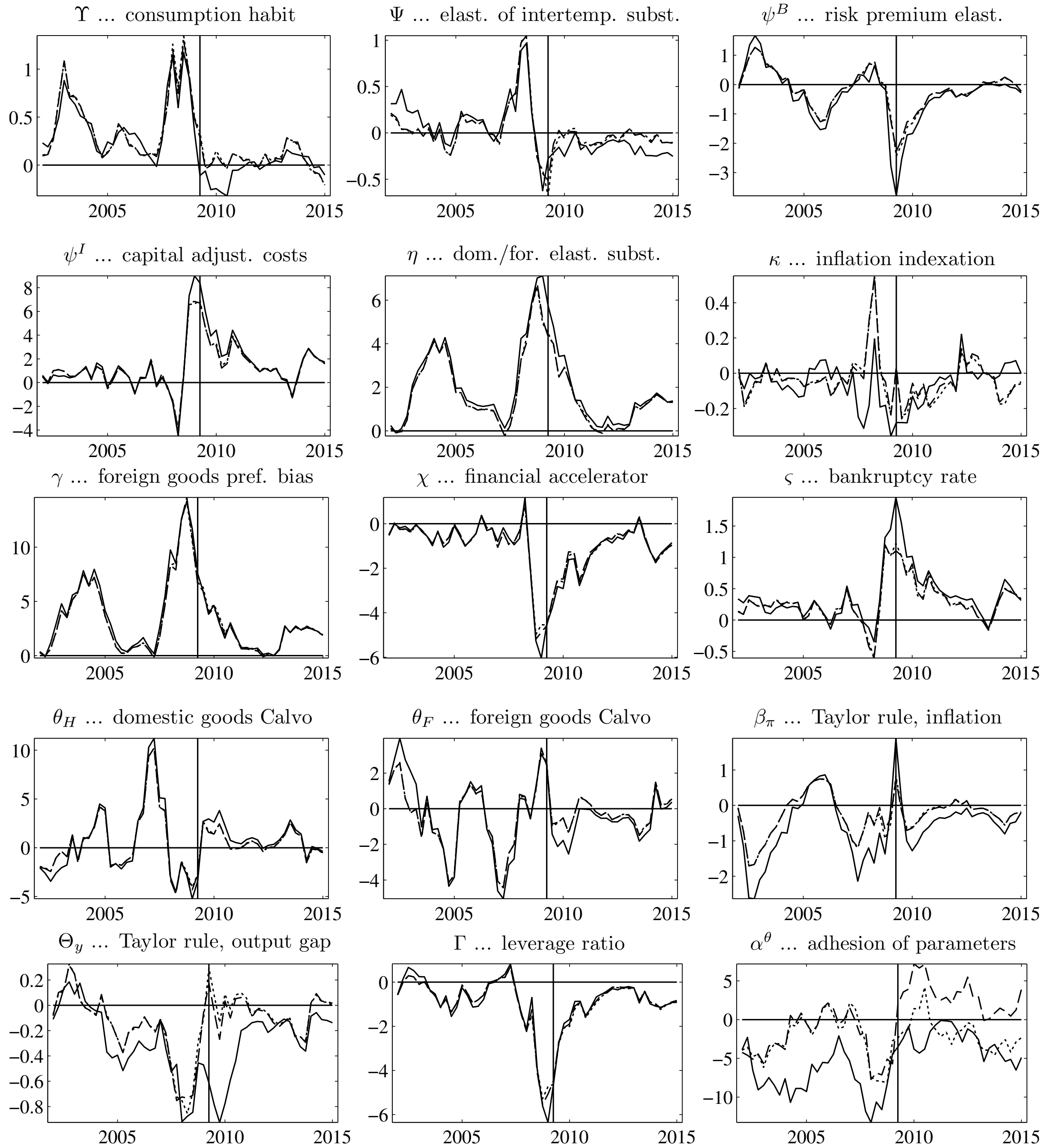
For the remaining economies, the results of the sensitivity exercise comparing the different calibrations of the adhesion parameter show similar results. Only in case of the Slovak economy, the trajectories of some time-varying parameters that were identified using the calibration of $\alpha_0^\theta = 0.1$ deviate more significantly from the baseline results after the onset of the crisis and the euro adoption. Most notably this concerns the parameters of foreign goods preference bias γ and the elasticity of substitution between domestic and foreign goods η. These results would suggest that both the parameters further increased after the euro adoption until 2011, when they started to return to their initial values. Perhaps, the baseline calibration is too tight for the Slovak economy, that underwent much deeper structural changes during the crisis than the remaining examined economies. Hence, the changes of the two structural parameters indicated by the nonlinear particle filter with calibration $\alpha_0^\theta = 0.1$ might be closer to the true situation.

6.2 Selection of time-varying parameters

Comparison of the filtered trajectories of the time-varying parameters conditional on the choice of time-varying and time-invariant model parameters is presented in Figure 6.2. Most of the trajectories of the time-varying structural parameters were nearly unaffected by the enlargement of the subset of time-varying model parameters. Only the trajectory of the output gap weight in the Taylor rule changed distinctively after the enlargement. This was caused by the fact that the smoothing parameter was considered constant in the baseline specification and was included in the subset of time-varying parameters with the shock AR(1) parameters. Since the smoothing parameter appears only in the interest rate rule it influenced the filtration of remaining time-varying parameters in that equation to certain extent.

In the remaining examined economies, the sensitivity exercise confirms the stability of the filtered trajectories irrespective of the selection of the subset of time-varying parameters. The only exception is the Slovak economy, where the addition of the shock AR(1) parameters lead to a serious deviation from the baseline trajectories after the euro adoption and monetary policy switch. For some parameters the trajectories change only marginally, while for other their development is completely reversed. Again, the compounded nature of the structural changes in the Slovak economy in the period of the Great Recession make the problem of their identification much more complicated. It is unclear which specification should be preferred.

Figure 6.2: NPF sensitivity to time-varying parameters selection, CZ



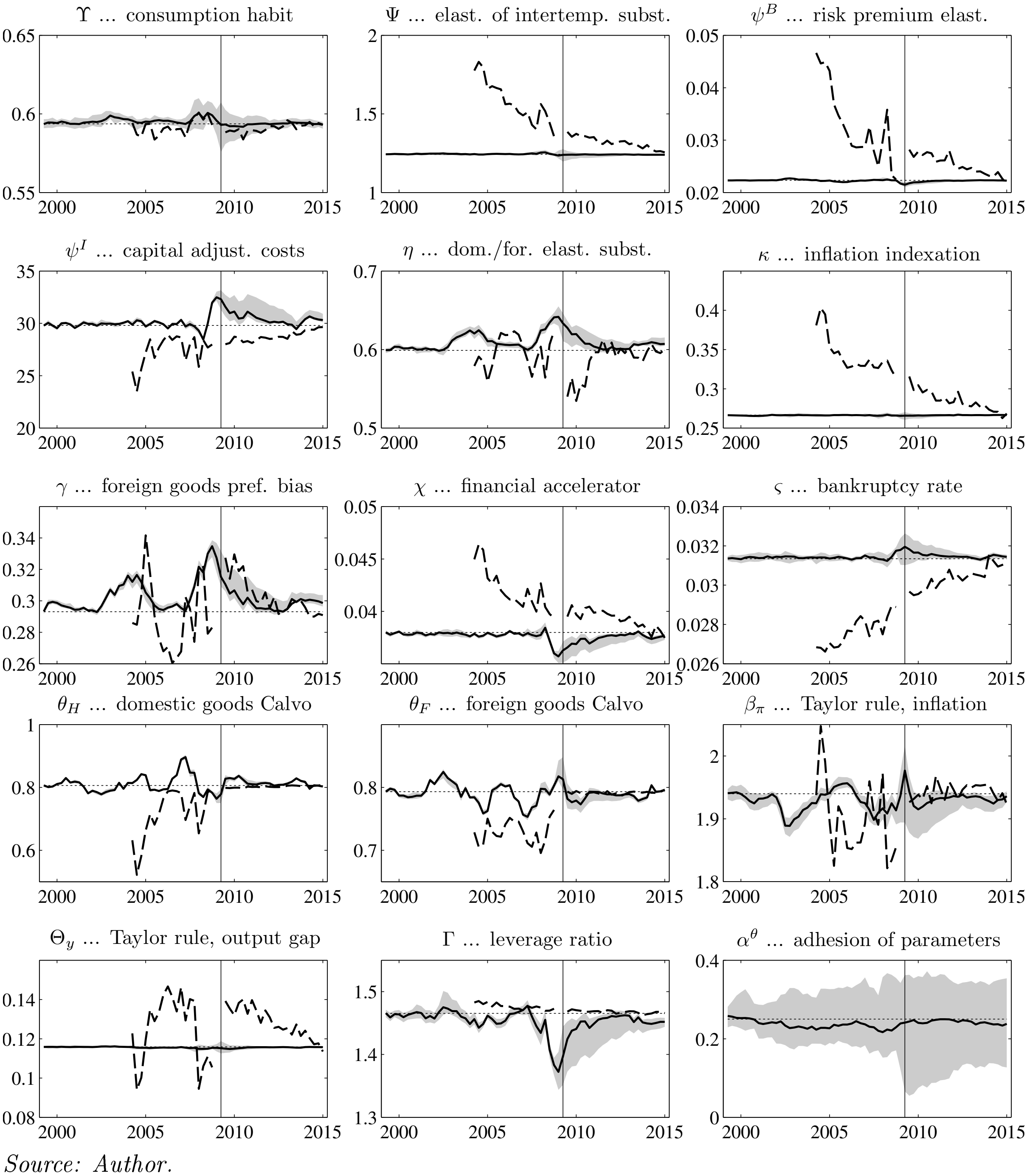
Source: Author.

Note: Percentage deviations from initial values are depicted, solid line - structural parameters, dashed line - structural parameters + AR, dotted line - structural parameters + AR + SVAR, vertical line - 2009Q1.

6.3 Comparison with recursive estimation

In this section, we compare the recursive estimates of model parameters to the time-varying parameter estimates obtained by the nonlinear particle filter. Figure 6.3 shows the comparison for the model of the Czech economy. In some cases both the approaches yield similar results. It is the consumption habit Υ and the foreign goods preference bias γ parameters that show similar development to a certain extent. For most of the remaining parameters the estimated trajectories differ significantly. Often, the recursive estimates show a distinct trend behaviour. This can be a manifestation of the structural change in the modelled economy but more often it is caused by the convergence of the recursive estimate from the prior mean to its long-run posterior estimate based on the information in the whole data sample. Thus, the recursive estimation approach is not appropriate for the identification of the structural changes using such a short time-series that are available for the Visegrád economies.

Figure 6.3: NPF vs. recursive estimation, CZ



Source: Author.

Note: Solid line - NPF estimates, dashed line - recursive estimates, vertical line - 2009Q1.

The same discrepancy between the trajectories of the time-varying parameters identified by the nonlinear particle filter and the recursive estimation arises also in the case of the remaining examined economies. Since the length of the data sample is the same for all the economies, this is not surprising. However, even in the case that long time-series were available for the examined economies, the results of this type of recursive estimation would tell us little about the current value of the structural parameter in given period, because the estimate would be based on the whole known history up to that period. Therefore, it would correspond more to the average characteristic of the economy in the past than to the current state of the economy. In case of the particle filter, this is not the case as the filtered values of the time-varying parameters correspond to the current structure of the economy.

In some economies, the recursive estimation algorithm failed to calculate the posterior estimates in some periods. Note the missing values in the graphs depicting the results of the recursive estimation. Usually, this problem occurred in the early phase of the Great Recession when the crisis struck, which coincidentally, would be the most interesting period for further analysis. There was a problem with the numerical optimization during the search for the posterior mode. Consequently, the Random Walk Metropolis-Hastings algorithm could not be initiated.

Even though the obtained results of the recursive estimation did not show many similarities to the results obtained by the nonlinear particle filter, the particle filter appears to be more robust and reliable tool for this kind of analysis.

Conclusion

It was the general goal of this thesis to identify the main factors that explain the differences in the macroeconomic development of the Visegrád economies during the Great Recession and subsequent recovery. For that purpose I chose a model approach and estimated five small open economy DSGE models with financial frictions for the four Visegrád economies and the euro area economy as a benchmark of a developed market economy. The model structure was broadly based on Shaari (2008) but several changes to the original structure were made. Most importantly, in case of the Slovak economy, deterministic monetary policy regime switch was incorporated into the model in order to model the euro adoption in Slovakia in January 2009.

The first intermediate goal, to identify long-run differences in the structure and behaviour of the Visegrád economies, was accomplished using estimated DSGE models with time-invariant parameters. The model parameters were estimated using the Random Walk Metropolis-Hastings algorithm. The posterior means of the model parameters that represent the economic structure were compared and discussed. The long-run behaviour characteristics were described and compared based on the impulse response functions.

The second intermediate goal, to identify short-run differences in the structure and behaviour of the Visegrád economies, was achieved with the use of nonlinear particle filter. The particle filter was used to estimate the trajectories of the time-varying structural parameters of the examined economies. A law of motion for the time-varying model parameters was specified as a weighted average of a random walk component and a white noise around the initial value of given parameter. The trajectories of the time-varying structural parameters were discussed and compared. Based on the filtered time-varying model parameters, a time-varying impulse response functions of the model economy were calculated next. The focus was set at the impulse responses of the real output as the most important macroeconomic variable that is of the greatest interest to the professionals and public as well. The main similarities and differences in the development of the impulse responses, especially during the crisis period, were discussed in the thesis.

The third intermediate goal, to compare the incidence and impacts of the exogenous shocks in the Visegrád countries, was fulfilled with the use filtered shock innovations and historical shock decomposition. The shock decomposition of the main macroeconomic variables: real output, CPI inflation, nominal interest rate and real exchange rate were presented and discussed. The shock decompositions showed which shocks were determining for the development during the crisis and what are the main driving forces of given economic variables.

The results of estimation with time-invariant structural parameters showed overall similarity of the Visegrád economies and especially of the Czech and Slovak economy. The similarity of the estimated parameters in the financial sector can be explained by the fact, that most commercial banks operating in the Visegrád economies are subsidiaries of large international groups, which treat the CEE (Central and Eastern Europe) markets in a similar way, and that the regulatory framework in the European union is to a large extent homogeneous.

One of the important differences between the examined economies was identified in the Czech economy, where the risk-premium elasticity is estimated to be about half as high as in the remaining Visegrád economies. This finding suggests that the real exchange rate of the Czech currency develops relatively moderately in comparison to the domestic currencies of other Visegrád economies. This regional safe haven status of the Czech currency explains its relatively limited depreciation during the Great Recession, which exacerbated the impact of the downfall of foreign demand on the and prolonged the recession in the Czech economy. Also, the weight of output gap in the Taylor rule of the Czech central bank is estimated to be about half as high asin the remaining Visegrád economies, while the weight of the CPI inflation is estimated to be very similar across all the examined economies. This result suggests that the nominal interest rate was not lowered as sharply in the Czech economy, which could be another reason, why the real exchange rate of the Czech currency remained relatively strong during the crisis.

The Polish economy benefited from its relatively low openness during the Great Recession that reduced the impact of the negative foreign demand shock on its economic performance. At the same time, the effect of declining foreign demand was largely compensated by substantial real exchange rate depreciation.

In the Slovak economy, the adoption of the euro currency excluded the unilateral depreciation of the domestic currency. Therefore, the immediate downturn of the Slovak economy at the onset of the crisis was deeper than in the remaining Visegrád economies. Later on, positive effects of the euro adoption materialized. According to the historical shock decomposition, the euro adoption lead to an improvement of the competitiveness of the Slovak economy and the declining foreign demand was to a large extent compensated by growing market shares of the Slovak exporters.

The historical shock decomposition also revealed sizeable negative effects of the monetary policy shocks on the real economic output in the Hungarian economy during the crisis. The monetary policy stance in Hungary was distinctively restrictive during the early phase of the Great Recession due to a large share of foreign currency denominated debt. In order to keep the foreign debt burden bearable, the Hungarian central bank had to keep the policy interest rates relatively high to prevent domestic currency depreciation.

The estimation of time-varying model parameters showed statistically significant changes of the Calvo parameters and steady-state leverage ratio of the entrepreneurs in all the examined economies. The obtained results suggest that the pricing and the attitude of the firms to the debt taking in the Visegrád economies changed quite significantly during the Great Recession. Interesting changes of the foreign goods preference bias or elasticity of substitution between domestic and foreign goods were also identified in most of the examined economies.

In the Czech economy, the changes of the structural parameters increasingly deviated from their initial values between 2007 and 2009. Thus, the structural changes in the Czech economy during the Great Recession could be interpreted as a correction and return to the long run economic structure. The structural changes in the Czech economy during the Great Recession amplified its responsiveness to the productivity shocks while at the same time dampening its responsiveness to the law of one price shocks and net worth shocks. Both these shocks negatively influenced the development of the Czech economy in this period.

The identified substantial downturn of domestic price stickiness after the euro adoption in the Slovak economy suggests that resetting and rounding of prices probably happened to some extent in this period.

The fourth goal of the thesis, to formulate recommendations for the monetary policy, was not explicitly discussed in the main text and will be carried out now. In the thesis, I showed that, while not as significant as in the euro area, the financial frictions can be an important driver of the aggregate output in the Visegrád economies. Not only does the financial accelerator mechanism amplify the exogenous shocks in the economy, but the financial sector itself can be a source of disturbances. In the baseline model with time-invariant structure I modelled these disturbances as exogenous shocks to the effective survival rate of entrepreneurs, which influences the development of the entrepreneurial net worth. However, in the model with time-varying parameters I have shown that the disturbances in the financial sector can originate in other areas as well. We have seen that the elasticity of the external finance premium with respect to the leverage ratio and the steady state leverage ratio itself can deviate from their long-run values quite markedly. Since the developments in the financial sector have direct impact on the development of the spread between the policy interest rate and the commercial interest rates, that the subjects in the economy actually face, the central banks have to monitor the situation in the financial sector closely. It is not sufficient to adjust the policy interest rate according to the current macroeconomic conditions, especially in an environment of near-zero interest rates. The central bank has to monitor and influence the behaviour of the commercial banks via other tools as well in order to achieve desired changes in their lending rates. This finding is in line with current trend of increasing importance of the macroprudential policy standards and development of the institutions of financial system oversight in the euro area as well as in the Visegrád economies.

Generally, the assumption of time-invariant underlying economic structure may be too simplifying. The results presented in the thesis suggest that, while some parameters may indeed be time-invariant, there are also parameters, such as the foreign goods preference bias (openness parameter), Calvo parameters, capital adjustment costs or the financial sector parameters, that can deviate from their initial values quite considerably at certain times, which influences the behaviour of the model economy. It was shown in the thesis that the nonlinear particle filter is a relatively robust tool, that can be used to identify these short-term changes in the economic structure. Unlike in the case of recursive estimation, additional assumptions about the law of motion of the time-varying parameters can be imposed on the model economy. Also, only a subset of the model parameters can be chosen to be time-varying, while in the recursive estimation all the model parameters are re-estimated in each period. Compared to the recursive estimation, the interpretation of a filtered time-varying parameter trajectory is better and more straightforward, because the values represent just the value in given period and not an average over the known past up to the given period as is the case of recursive estimation. Therefore, it is the main contribution of this thesis that it explored the applicability and robustness of the nonlinear particle filter algorithm using the real world examples of the Visegrád economies and the euro area during the turbulent period of the Great Recession.

Further research should be aimed at exploration of the properties of nonlinear particle filter algorithm and its ability to identify the time-varying structure of the DSGE models with more severe nonlinearities. The nonlinear particle filter could then be extended to take into account a third-order approximation of the nonlinear DSGE model. According to Binning (2013), a second-order approximation introduces a constant correction for the effects of risk, whereas a third-order approximation introduces a time varying risk term and an additional control for the effects of skewed shocks. Apart from the potential structural changes it could be interesting to explore the effects of different kurtosis and skewness of the exogenous innovations distributions. Another direction for further research could be to employ the nonlinear particle filter algorithm to estimate the time-variyng structure of different DSGE model specifications that contain, for example, more elaborate labour market, more comprehensive structure of intermediate and final goods production in the domestic economy or more complex foreign block. In case of the Slovak economy, it would be desirable to further explore the possibilities how to implement the euro adoption and monetary policy regime switch as an anticipated structural change along the lines of Kulish and Pagan (2014) and estimate other unexpected structural changes using the nonlinear particle filter at the same time.

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List of Figures

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Appendix A

Notation

p	probability density
$p(A\|B)$.	conditional probability density of A, depending on B
$iid(0,\sigma^2)$	independent and identically distributed random variables, zero mean and variance σ^2
$N(\mu,\sigma^2)$	normal Gaussian distribution of probability, mean μ and variance σ^2
$f_N(\mu,\Sigma)$	normal probability density function, mean μ and covariance matrix Σ
$\mathcal{L}$	likelihood function
$\mathcal{K}$	likelihood kernel
$'$	transposition operator
$\otimes$	Kronecker product operator
t	time index
E_t	expectations at time t operator
X_t	real variable, level
$\widetilde{X}_t$	nominal variable, level
$\overline{X}$	steady-state variable, level
x_t	real variable, logarithmic deviation from steady state, $x_t = \log\left(\frac{X_t}{\overline{X}}\right)$
$\widetilde{x}_t$	nominal variable, logarithmic deviation from steady state, $\widetilde{x}_t = \log\left(\frac{\widetilde{X}_t}{\overline{X}}\right)$

Endogenous variables

y_t	aggregate output
c_t	aggregate consumption
inv_t	aggregate investment
k_t	capital stock
r_t	policy nominal interest rate
rer_t	real exchange rate (CZK/EUR)
s_t	nominal exchange rate (CZK/EUR)
d_t	domestic bonds
b_t	foreign bonds
π_t^r	profits of retail firms
tr_t	transfers
z_t	net foreign assets position
π_t	CPI inflation rate

p_t .... CPI index
$p_{H,t}$ ..... price index of home goods
$p_{F,t}$ ..... price index of foreign goods
tot_t ..... terms of trade
mc_t ..... domestic marginal costs
$l_{H,t}$ ..... households' labour supply
$w_{H,t}$ .... households' wage
$w_{E,t}$ .... entrepreneurs' wage
$r_{G,t}$ ..... gross rental rate of capital
$r_{K,t}$ ..... gross return to capital investment
q_t .... real price of capital
n_t ...... enterpreneur's net-worth
efp_t .... external finance premium
sw_t ..... regime switch

Exogenous variables
y_t^* ...... foreign aggregate output
π_t^* ...... foreign CPI inflation rate
r_t^* ...... foreign nominal interest rate
lop_t ..... law of one price gap shock
a_t^{NW} .... net worth shock
a_t^{UIP} .... debt-elastic risk premium shock
a_t^Y ...... domestic productivity shock
$\varepsilon_t^{y^*}$ ...... foreign aggregate output innovation
$\varepsilon_t^{\pi^*}$ ..... foreign CPI inflation innovation
$\varepsilon_t^{r^*}$ ...... foreign interest rate innovation
ε_t^{LOP} .... law of one price gap innovation
ε_t^{NW} .... entrepreneurial net worth innovation
ε_t^{UIP} .... debt elastic risk premium innovation
ε_t^Y ...... domestic productivity innovation
ε_t^{MP} .... monetary policy innovation
ε_t^{SW} .... regime switch innovation

Structural parameters
β .... discount parameter
Υ .... external habit in consumption
Ψ .... inverse elasticity of labour supply
ε .... elasticity of substitution between goods varieties
η .... elasticity of substitution between home and foreign goods
γ .... preference bias to the foreign goods
α .... capital share in production
ω .... share of entrepreneurs in aggregate labour supply
μ .... steady state markup, inverted marginal costs
δ .... depreciation rate of capital
ψ^I ...... capital adjustment costs parameter
ψ^B ..... elasticity of risk premium
θ_H ...... Calvo parameter of home goods
θ_F ...... Calvo parameter of foreign goods
κ .... inflation indexation parameter

χ .... financial accelerator parameter
ς .... entrepreneurs' bankruptcy rate
Γ .... steady-state ratio of capital and net-worth
ρ .... Taylor rule - smoothing parameter
β_π ...... Taylor rule - weight of inflation
Θ_y ...... Taylor rule - weight of output gap

Shock parameters
ρ_{UIP} .... AR(1) parameter of debt-elastic risk premium shock
ρ_{LOP} ... AR(1) parameter of law of one price gap shock
ρ_{NW} .... AR(1) parameter of entrepreneurial net worth shock
ρ_Y ...... AR(1) parameter of domestic productivity shock
ρ_{SW} .... AR(1) parameter of regime switch shock
$\rho_{y^*y^*}$ .... VAR(1) - interaction of y_t^* and y_{t-1}^*
$\rho_{\pi^*\pi^*}$ .... VAR(1) - interaction of π_t^* and π_{t-1}^*
$\rho_{r^*r^*}$ .... VAR(1) - interaction of r_t^* and r_{t-1}^*
$\rho_{y^*\pi^*}$ .... VAR(1) - interaction of y_t^* and π_{t-1}^*
$\rho_{y^*r^*}$ .... VAR(1) - interaction of y_t^* and r_{t-1}^*
$\rho_{\pi^*y^*}$ .... VAR(1) - interaction of π_t^* and y_{t-1}^*
$\rho_{\pi^*r^*}$ .... VAR(1) - interaction of π_t^* and r_{t-1}^*
$\rho_{r^*y^*}$ .... VAR(1) - interaction of r_t^* and y_{t-1}^*
$\rho_{r^*\pi^*}$ .... VAR(1) - interaction of r_t^* and π_{t-1}^*
$\sigma_{\pi^*y^*}$ .... VAR(1) - interaction of $\varepsilon_t^{\pi^*}$ and $\varepsilon_t^{y^*}$
$\sigma_{r^*y^*}$ .... VAR(1) - interaction of $\varepsilon_t^{r^*}$ and $\varepsilon_t^{y^*}$
$\sigma_{r^*\pi^*}$ .... VAR(1) - interaction of $\varepsilon_t^{r^*}$ and $\varepsilon_t^{\pi^*}$
σ_{UIP} .... standard deviation of debt-elastic risk premium innovations
σ_{LOP} ... standard deviation of law of one price gap innovations
σ_{NW} .... standard deviation of entrepreneurial net worth innovations
σ_Y ...... standard deviation of domestic productivity innovations
σ_{MP} .... standard deviation of monetary policy innovations
σ_{SW} .... standard deviation of regime switch innovations
σ_{y^*} ..... standard deviation of foreign aggregate output innovations
σ_{π^*} ..... standard deviation of foreign CPI inflation innovations
σ_{r^*} ..... standard deviation of foreign interest rate innovations

Appendix B

Derivations

B.1 Definitions

B.1.1 Choice between goods varieties

Since the foreign goods index is perfect analogue to the home goods index, we will derive the results only for home goods. Note that all the results for home goods hold similarly for foreign goods.

In each period the representative household's budget M_t is limited and the prices of goods $P_{H,t}(h)$ are given. The representative household solves following optimization problem

$$\max_{\{C_{H,t}(h)\}_{h\in\langle 0,1\rangle}} C_{H,t} - \lambda_{H,t}\left(\int_0^1 C_{H,t}(h)P_{H,t}(h) - M_t\right).$$

The first order condition is

$$C_{H,t}(h) = \frac{\lambda_{H,t}^{-\varepsilon} P_{H,t}(h)^{-\varepsilon}}{C_{H,t}}$$

and so between any two varieties following relation has to hold

$$C_{H,t}(i) = \left(\frac{P_{H,t}(i)}{P_{H,t}(j)}\right)^{-\varepsilon} C_{H,t}(j). \tag{B.1.1}$$

Substituting into the constraint we receive

$$\frac{C_{H,t}(j)}{P_{H,t}(j)^{-\varepsilon}} \int_0^1 P_{H,t}(i)^{1-\varepsilon}\,\mathrm{d}i = M_t.$$

We now define the home goods price index as

$$P_{H,t} = \left(\int_0^1 P_{H,t}(i)^{1-\varepsilon}\,\mathrm{d}i\right)^{\frac{1}{1-\varepsilon}} \tag{B.1.2}$$

and simplify the previous equation to

$$C_{H,t}(j) = \frac{M_t P_{H,t}^{\varepsilon-1}}{P_{H,t}(j)^{\varepsilon}}.$$

Substituting this result into the home goods consumption index definition (3.1.2) we obtain

$$C_{H,t} = \left\{\int_0^1 \left[\frac{M_t}{P_{H,t}}\left(\frac{P_{H,t}}{P_{H,t}(j)}\right)^{\varepsilon}\right]^{\frac{\varepsilon-1}{\varepsilon}}\,\mathrm{d}j\right\}^{\frac{\varepsilon}{\varepsilon-1}},$$

which can be simplified to

$$C_{H,t} = \left(\frac{M_t}{P_{H,t}}\right) \left(\int_0^1 P_{H,t}(j)^{-\varepsilon \cdot \frac{\varepsilon-1}{\varepsilon}} \,\mathrm{d}j \, P_{H,t}^{\varepsilon-1}\right)^{\frac{\varepsilon}{\varepsilon-1}}$$

and the result is

$$C_{H,t} = \frac{M_t}{P_{H,t}}.$$

Plugging for M_t in (B.1.1) we receive the demand function for particular variety of home goods

$$C_{H,t}(j) = C_{H,t} \left(\frac{P_{H,t}(j)}{P_{H,t}}\right)^{-\varepsilon}. \tag{B.1.3}$$

B.1.2 Choice between home and foreign goods

The representative household has also to choose optimal combination of home and foreign goods in each period. The budget M_t and price indices $P_{H,t}$ and $P_{F,t}$ (both expressed in domestic currency) are given. The optimization problem takes following form

$$\max_{C_{H,t}, C_{F,t}} C_t - \lambda_t \left(C_{H,t} P_{H,t} + C_{F,t} P_{F,t} - M_t\right).$$

The first order conditions are as follows

$$\frac{C_t}{C_{H,t}}(1-\gamma) = \lambda_t^\eta P_{H,t}^\eta,$$

$$\frac{C_t}{C_{F,t}}\gamma = \lambda_t^\eta P_{F,t}^\eta.$$

This means that we can express the home goods index as

$$C_{H,t} = C_{F,t} \frac{1-\gamma}{\gamma} \left(\frac{P_{H,t}}{P_{F,t}}\right)^{-\eta}$$

and substitute into the constraint. This yields

$$C_{F,t} \frac{1-\gamma}{\gamma} \left(\frac{P_{H,t}}{P_{F,t}}\right)^{-\eta} P_{H,t} + C_{F,t} P_{F,t} = M_t,$$

which can be simplified to

$$C_{F,t}\left[(1-\gamma) P_{H,t}^{1-\eta} + \gamma P_{F,t}^{1-\eta}\right] = \gamma M_t P_{F,t}^{-\eta}.$$

Now we define the consumer price index P_t as

$$P_t = \left[(1-\gamma) P_{H,t}^{1-\eta} + \gamma P_{F,t}^{1-\eta}\right]^{\frac{1}{1-\eta}}. \tag{B.1.4}$$

The previous equation, therefore, simplifies to

$$C_{F,t} P_t^{1-\eta} = \gamma M_t P_{F,t}^{-\eta}$$

and the home and foreign goods consumption indices can be expressed as

$$C_{H,t} = (1-\gamma) M_t P_{H,t}^{-\eta} P_t^{\eta-1}, \tag{B.1.5}$$

$$C_{F,t} = \gamma M_t P_{F,t}^{-\eta} P_t^{\eta-1}. \tag{B.1.6}$$

Substituting these results into the consumption index definition (3.1.1) we obtain

$$C_t = (1-\gamma)^{\frac{1}{\eta}} \left[M_t(1-\gamma)P_{H,t}^{-\eta}P_t^{\eta-1}\right]^{\frac{\eta-1}{\eta}} + \gamma^{\frac{1}{\eta}} \left(\gamma M_t P_{F,t}^{-\eta} P_t^{\eta-1}\right)^{\frac{\eta-1}{\eta}}$$

and after some algebra we receive following result

$$C_t = \frac{M_t}{P_t}.$$

Plugging for M_t in (B.1.5) and (B.1.6) we receive the home and foreign goods demand functions,

$$C_{H,t} = C_t(1-\gamma)\left(\frac{P_{H,t}}{P_t}\right)^{-\eta}, \tag{B.1.7}$$

$$C_{F,t} = C_t\gamma\left(\frac{P_{F,t}}{P_t}\right)^{-\eta}. \tag{B.1.8}$$

B.2 Households

Formally, the representative household's dynamic optimization problem can be summarized as

$$\max_{\{C_t, L_{H,t}, D_t, B_t\}_{t=0}^{\infty}} E_0\Bigg\{\sum_{t=0}^{\infty}\beta^t\Big[U(C_t, C_{t-1}, L_{H,t}) - \lambda_t^{BC}\big(\widetilde{W}_{H,t}L_{H,t} + R_{t-1}D_{t-1} + \\ + R_{t-1}^*\Psi^B(Z_{t-1}, A_{t-1}^{UIP})S_tB_{t-1} + \Pi_t^r + TR_t - P_tC_t - D_t - S_tB_t\big)\Big]\Bigg\}. \tag{B.2.1}$$

Derivating the Lagrangian (B.2.1) with respect to $C_t, L_{H,t}, D_t$ and B_t for any given t we receive following first order conditions:

$$[L_{H,t}]: \quad \widetilde{W}_{H,t} = -\frac{L_{H,t}^{\Psi}}{\lambda_t^{BC}}, \tag{B.2.2}$$

$$[C_t]: \quad \frac{1}{C_t - \Upsilon C_{t-1}} = -\lambda_t^{BC}P_t, \tag{B.2.3}$$

$$[B_t]: \quad \lambda_t^{BC}S_t = \lambda_{t+1}^{BC}\beta R_t^*\Psi^B(Z_t, A_t^{UIP})S_{t+1}, \tag{B.2.4}$$

$$[D_t]: \quad \lambda_t^{BC} = \lambda_{t+1}^{BC}\beta R_t. \tag{B.2.5}$$

Combining (B.2.2) and (B.2.3) we get labour supply relation:

$$\frac{\widetilde{W}_{H,t}}{P_t} = W_{H,t} = L_{H,t}^{\psi}(C_t - \Upsilon C_{t-1}). \tag{B.2.6}$$

By combination of (B.2.3) and (B.2.5) we derive the optimal choice between consumption and domestic bonds:

$$R_t = \frac{1}{\beta}\frac{C_{t+1} - \Upsilon C_t}{C_t - \Upsilon C_{t-1}}\frac{P_{t+1}}{P_t}. \tag{B.2.7}$$

Similarly, combining (B.2.3) and (B.2.4) we can derive the optimal choice between consumption and foreign bonds:

$$R_t^*\Psi^B(Z_t, A_t^{UIP}) = \frac{1}{\beta}\frac{S_t}{S_{t+1}}\frac{(C_{t+1} - \Upsilon C_t)}{(C_t - \Upsilon C_{t-1})}\frac{P_{t+1}}{P_t} \tag{B.2.8}$$

Equations (B.2.7) and (B.2.8) imply optimal choice between foreign and domestic bonds:

$$\begin{aligned} R_t^* \Psi^B(Z_t, A_t^{UIP}) &= \frac{S_t}{S_{t+1}} R_t, \\ R_t^* \exp\left[-\psi^B(Z_t + A_t^{UIP})\right] &= R_t \frac{RER_t P_t}{P_t^*} \frac{P_{t+1}^*}{P_{t+1} RER_{t+1}}, \end{aligned} \tag{B.2.9}$$

which is a risk-adjusted uncovered interest parity (UIP) condition.

B.3 Entrepreneurs

B.3.1 Intermediate goods production

The representative entrepreneur takes nominal factor prices as well as the wholesale price $P_{H,t}^W$ as given. Therefore, each period he solves following optimization problem

$$\min_{L_{H,t},K_t} \widetilde{R}_{G,t} K_t + L_{H,t} \widetilde{W}_{H,t} + \widetilde{W}_{E,t} - \lambda_t^{PF} \left(Y_{H,t} - A_t^Y K_t^\alpha L_{H,t}^{\Omega(1-\alpha)} \right),$$

where $\widetilde{R}_{G,t}$ is the gross nominal rental rate for capital, $\widetilde{W}_{H,t}$ is the nominal wage paid to households and $\widetilde{W}_{E,t}$ is the nominal wage paid to entrepreneurs themselves. The first order conditions of this problem are:

$$\begin{aligned} \widetilde{R}_{G,t} &= \lambda_t^{PF} \alpha \frac{Y_{H,t}}{K_t}, \\ \widetilde{W}_{H,t} &= \lambda_t^{PF} \Omega(1-\alpha) \frac{Y_{H,t}}{L_{H,t}}, \\ \widetilde{W}_{E,t} &= \lambda_t^{PF} (1-\Omega)(1-\alpha) \frac{Y_{H,t}}{L_{E,t}}. \end{aligned}$$

Since the firm operates at zero profit conditions[1] and λ_t^{PF} represents the nominal marginal cost of producing one additional unit of output $\widetilde{MC}_{H,t}$, it is equal to the wholesale price $P_{H,t}^W$. Also, $L_{E,t}$ is equal to 1 by assumption. Thus, we can rewrite the first order conditions in a following way

$$\widetilde{R}_{G,t} = P_{H,t}^W \alpha \frac{Y_{H,t}}{K_t}, \tag{B.3.1}$$

$$\widetilde{W}_{H,t} = P_{H,t}^W \Omega(1-\alpha) \frac{Y_{H,t}}{L_{H,t}}, \tag{B.3.2}$$

$$\widetilde{W}_{E,t} = P_{H,t}^W (1-\Omega)(1-\alpha) Y_{H,t}. \tag{B.3.3}$$

Following Shaari (2008), the effect of law of one price gap and real exchange rate on the factor prices can be demonstrated. We have already shown that the nominal marginal costs are equal to the wholesale price. This implies that the real marginal costs can be expresses as

$$MC_{H,t} = \frac{\widetilde{MC}_{H,t}}{P_{H,t}} = \frac{P_{H,t}^W}{P_{H,t}}. \tag{B.3.4}$$

[1] At perfectly competitive markets the profit maximizing condition require that the nominal marginal costs of production equal the price, i.e. $\widetilde{MC}_t = P_t$. At this particular market this implies $\lambda_t^{PF} = \widetilde{MC}_{H,t} = P_{H,t}^W$.

Dividing the equations (B.3.1), (B.3.2) and (B.3.3) by the CPI index P_t and substituting for $P_{H,t}^W$ from (B.3.4) we receive

$$\begin{aligned}
\frac{\widetilde{R}_{G,t}}{P_t} &= R_{G,t} = \alpha \frac{Y_{H,t}}{K_t} MC_{H,t} \frac{P_{H,t}}{P_t}, \\
\frac{\widetilde{W}_{H,t}}{P_t} &= W_{H,t} = \Omega(1-\alpha) \frac{Y_{H,t}}{L_{H,t}} MC_{H,t} \frac{P_{H,t}}{P_t}, \\
\frac{\widetilde{W}_{E,t}}{P_t} &= W_{E,t} = (1-\Omega)(1-\alpha) Y_{H,t} MC_{H,t} \frac{P_{H,t}}{P_t}.
\end{aligned}$$

B.3.2 Capital goods production

Log-linearizing the law of motion of capital (3.3.6) gives:

$$\begin{aligned}
\overline{K}(1+k_{t+1}) = \overline{K} + \Phi'\left(\frac{\overline{INV}}{\overline{K}}\right)\overline{K}\frac{\overline{I}}{\overline{K}} inv_t + (1-\delta)\overline{K}k_t + \Phi\left(\frac{\overline{INV}}{\overline{K}}\right)\overline{K}k_t - \\
- \Phi'\left(\frac{\overline{INV}}{\overline{K}}\right)\overline{K}\frac{\overline{I}}{\overline{K}^2}\overline{K}k_t, \\
\overline{K}k_{t+1} = \overline{K}\delta inv_t + (1-\delta)\overline{K}k_t + \delta\overline{K}k_t - \delta\overline{K}k_t, \\
k_{t+1} = \delta inv_t + (1-\delta)k_t.
\end{aligned}$$

When deciding about how much capital to produce, the entrepreneur solves following optimization problem

$$\max_{INV_t} \widetilde{Q}_t \Phi\left(\frac{INV_t}{K_t}\right) K_t - P_t INV_t.$$

The first order condition is

$$\widetilde{Q}_t \Phi'\left(\frac{INV_t}{K_t}\right) = P_t,$$

which implies

$$Q_t = \frac{\widetilde{Q}_t}{P_t} = \frac{1}{\Phi'\left(\frac{INV_t}{K_t}\right)}.$$

Since $\Phi'\left(\frac{INV_t}{K_t}\right) = 1 - \psi^I\left(\frac{INV_t}{K_t} - \delta\right)$, in log-linear terms we receive

$$q_t = \psi^I \delta(i_t - k_t). \tag{B.3.5}$$

B.3.3 Entrepreneurial net worth

During log-linearization of entrepreneurial equity definition (3.3.12) we employ several useful relations. From equation (3.3.9) shifted to time t we can express f_t,

$$f_t = \frac{\overline{K}(q_{t-1}+k_t) - \overline{N}n_t}{\overline{F}}$$

next, we use the steady-state version of equation (3.3.10)

$$\overline{R}_K = \left(\frac{\overline{N}}{\overline{QK}}\right)^{-\chi}\overline{R}$$

and we also log-linearize (3.3.11) and rearrange to receive

$$\overline{V}v_t = \frac{\overline{N}n_{t+1} - \overline{W}_E w_{E,t}}{1-\varsigma} - \overline{V}a_t^{NW}.$$

The log-linearized version of (3.3.12) can be then obtained in following way

$$\begin{aligned}\frac{\overline{N}n_{t+1} - \overline{W}_E w_{E,t}}{1-\varsigma} &= \overline{R}_K \overline{QK}\left(r_{K,t} + q_{t-1} + k_t\right) - \\ &- \left(\frac{\overline{N}}{\overline{QK}}\right)^{-\chi} \overline{RF}\left(-\chi n_t + \chi q_{t-1} + \chi k_t + r_{t-1} - \pi_t + f_t\right) + \overline{V}a_t^{NW}\end{aligned}$$

now, using the fact that $\overline{Q} = 1$, $\overline{F} = \overline{K} - \overline{N}$ and $\overline{V} = \overline{R}_K\overline{N}$ we can simplify to

$$\begin{aligned}\frac{\overline{N}n_{t+1} - \overline{W}_E w_{E,t}}{1-\varsigma} = \overline{R}_K \Big[&\overline{K}\left(r_{K,t} + q_{t-1} + k_t\right) - \\ &- (\overline{K} - \overline{N})\left(-\chi n_t + \chi q_{t-1} + \chi k_t + r_{t-1} - \pi_t\right) - \\ &- \overline{K}(q_{t-1} + k_t) + \overline{N}n_t + \overline{N}a_t^{NW}\Big]\end{aligned}$$

express n_{t+1}

$$\begin{aligned}n_{t+1} = (1-\varsigma)\overline{R}_K \Big[&\frac{\overline{K}}{\overline{N}}\left(r_{K,t} + q_{t-1} + k_t\right) - \frac{\overline{K} - \overline{N}}{\overline{N}}\left(-\chi n_t + \chi q_{t-1} + \chi k_t + r_{t-1} - \pi_t\right) - \\ &- \frac{\overline{K}}{\overline{N}}(q_{t-1} + k_t) + n_t + a_t^{NW}\Big] + \frac{\overline{W}_E}{\overline{N}} w_{E,t}\end{aligned}$$

and simplify to

$$\begin{aligned}n_{t+1} = (1-\varsigma)\overline{R}_K &\left[\frac{\overline{K}}{\overline{N}} r_{K,t} - \frac{\overline{K} - \overline{N}}{\overline{N}}\left(\chi q_{t-1} + \chi k_t + r_{t-1} - \pi_t\right) + \left(\chi \frac{\overline{K} - \overline{N}}{\overline{N}} + 1\right) n_t + a_t^{NW}\right] + \\ &+ \frac{\overline{W}_E}{\overline{N}} w_{E,t}. \qquad \text{(B.3.6)}\end{aligned}$$

Using the substitution $\frac{\overline{K}-\overline{N}}{\overline{N}} = \Gamma$, $\frac{\overline{K}}{\overline{N}} = \Gamma + 1$ and $\frac{\overline{W}_E}{\overline{N}} = \frac{\overline{W}_E}{\overline{K}}\frac{\overline{K}}{\overline{N}} = (\Gamma + 1)\frac{\overline{W}_E}{\overline{K}}$ we can rewrite the equation (B.3.6) as

$$\begin{aligned}n_{t+1} = (1-\varsigma)\overline{R}_K &\left[(\Gamma + 1) r_{K,t} - \chi\Gamma(q_{t-1} + k_t) - \Gamma(r_{t-1} - \pi_t) + (\chi\Gamma + 1)n_t + a_t^{NW}\right] + \\ &+ (\Gamma + 1)\frac{\overline{W}_E}{\overline{K}} w_{E,t}. \qquad \text{(B.3.7)}\end{aligned}$$

B.4 Retailers

B.4.1 Phillips curve of home goods

Let $Y_{H,t}(z)$ be the home good sold by a retailer z in period t. In line with (3.1.2), the aggregate good sold to households by all the home goods retailers is given by CES function,

$$Y_{H,t} = \left(\int_0^1 Y_{H,t}(z)^{\frac{\varepsilon-1}{\varepsilon}}\, \mathrm{d}z\right)^{\frac{\varepsilon}{\varepsilon-1}}.$$

According to (B.1.3), expected future demands for the home goods of retailer z that has re-optimized its price at time t are given by

$$Y_{H,t+s}(z) = \left(\frac{P_{H,t}^{NEW}}{P_{H,t+s}} (\pi_{t-1,t+s-1})^{\kappa} \right)^{-\varepsilon} Y_{H,t+s}, \tag{B.4.1}$$

where $\pi_{t-1,t+s-1} = \log\left(\frac{P_{t+s-1}}{P_{t-1}}\right)$. The representative retailer, therefore, solves following optimization problem when re-optimizing its price,

$$\max_{P_{H,t}^{NEW}} E_t \sum_{s=0}^{\infty} \beta^s \theta_H^s \left[Y_{H,t+s}(z) \left(P_{H,t}^{NEW} (\pi_{t-1,t+s-1})^{\kappa} - P_{H,t+s}^{W} \right) \right].$$

Using the demand schedule (B.4.1) and the fact that $\frac{P_{H,t+k}^{W}}{P_{H,t+k}} = MC_{H,t+k}$, this can be rewritten in a following way

$$\max_{P_{H,t}^{NEW}} E_t \sum_{s=0}^{\infty} \beta^s \theta_H^s \left[\left(\frac{P_{H,t}^{NEW}}{P_{H,t+s}} (\pi_{t-1,t+s-1})^{\kappa} \right)^{-\varepsilon} Y_{H,t+s} \big(P_{H,t}^{NEW} (\pi_{t-1,t+s-1})^{\kappa} - \right.$$
$$\left. - P_{H,t+s} MC_{H,t+s} \big) \right].$$

The first order condition of this problem is

$$\sum_{s=0}^{\infty} \beta^s \theta_H^s E_t \left[Y_{H,t+s} \left(\frac{P_{H,t}^{NEW}}{P_{H,t+s}} (\pi_{t-1,t+s-1})^{\kappa} \right)^{-\varepsilon} \Big(P_{H,t}^{NEW} (\pi_{t-1,t+s-1})^{\kappa} + \right.$$
$$\left. + \frac{\varepsilon}{1-\varepsilon} P_{H,t+s} MC_{H,t+s} \Big) \right] = 0.$$

Log-linearizing this first order condition we receive

$$\sum_{s=0}^{\infty} \theta_H^s \beta^s E_t \left(p_{H,t}^{NEW} + \kappa p_{t+s-1} - \kappa p_{t-1} - p_{H,t+s} - mc_{H,t+s} \right) = 0$$

and isolating the $p_{H,t}^{NEW}$ we obtain

$$p_{H,t}^{NEW} = (1-\beta\theta_H) E_t \sum_{s=0}^{\infty} \theta_H^s \beta^s \left(\kappa p_{t-1} - \kappa p_{t+s-1} + p_{H,t+s} + mc_{H,t+s} \right).$$

This equation can be rewritten in a following way

$$p_{H,t}^{NEW} = (1-\beta\theta_H) E_t \sum_{s=1}^{\infty} \theta_H^s \beta^s \left[p_{H,t+s} + mc_{H,t+s} + \kappa \sum_{\tau=0}^{s-1} (p_{t+\tau-1} - p_{t+\tau}) \right] +$$
$$+ (1-\beta\theta_H)(p_{H,t} + mc_{H,t})$$

and using the definition of inflation (3.1.8) this means

$$p_{H,t}^{NEW} = (1-\beta\theta_H) E_t \sum_{s=1}^{\infty} \theta_H^s \beta^s \left(p_{H,t+s} + mc_{H,t+s} - \kappa \sum_{\tau=0}^{s-1} \pi_{t+\tau} \right) + \tag{B.4.2}$$
$$+ (1-\beta\theta_H)(p_{H,t} + mc_{H,t})$$

Now we subtract the equation (3.4.1) shifted to time $t-1$ from the original equation and receive

$$\pi_{H,t} = (1-\theta_H)p_{H,t}^{NEW} - (1-\theta_H)p_{H,t-1} + \theta_H\kappa\pi_{t-1}. \tag{B.4.3}$$

Plug the $p_{H,t}^{NEW}$ from (B.4.2) into the equation (B.4.3) to obtain

$$\begin{aligned}\pi_{H,t} = (1-\theta_H)(1-\beta\theta_H)E_t\sum_{s=1}^{\infty}\theta_H^s\beta^s\left(p_{H,t+s} + mc_{H,t+s} - \kappa\sum_{\tau=0}^{s-1}\pi_{t+\tau}\right)+ \\ + (1-\theta_H)(1-\beta\theta_H)(p_{H,t}+mc_{H,t}) - (1-\theta_H)p_{H,t-1} + \theta_H\kappa\pi_{t-1}.\end{aligned} \tag{B.4.4}$$

We can use the equation (B.4.1) shifted to time $t+1$ and plug it back into the original equation to get rid of the infinite sum, we receive

$$\begin{aligned}\pi_{H,t} = {} & \theta_H\beta E_t\pi_{H,t+1}+ \\ & + \theta_H\beta(1-\theta_H)(1-\theta_H\beta)E_t\left(p_{H,t+1} + mc_{H,t+1} - \kappa\pi_t\sum_{s=1}^{\infty}\theta_H^s\beta^s\right) - \\ & - \theta_H\beta(1-\theta_H)(1-\theta_H\beta)E_t(p_{H,t+1} + mc_{H,t+1})+ \\ & + (1-\theta_H)(1-\theta_H\beta)(p_{H,t}+mc_{H,t})+ \\ & + \theta_H\beta(1-\theta_H)p_{H,t} - (1-\theta_H)p_{H,t-1} - \kappa\theta_H^2\beta\pi_t + \kappa\theta_H\pi_{t-1}.\end{aligned}$$

Summing up the geometric series $\sum_{s=1}^{\infty}\theta_H^s\beta^s = \frac{1}{1-\theta_H\beta}$, rearranging the terms and using the fact that $p_{H,t} - p_{H,t-1} = \pi_{H,t}$ we find that the dynamics of home goods inflation can be approximated by following equation,

$$\pi_{H,t} = \beta E_t\pi_{H,t+1} - \kappa\beta\pi_t + \kappa\pi_{t-1} + \frac{(1-\theta_H)(1-\theta_H\beta)}{\theta_H}mc_{H,t}. \tag{B.4.5}$$

B.5 Market clearing and equilibrium

B.5.1 Net foreign assets

Since $Z_t = \frac{S_tB_t}{P_{H,t}Y_{H,t}}$, the evolution of net foreign assets position can be derived in a following way,

$$\begin{aligned}S_tB_t &= R_{t-1}^*\Psi^B(Z_{t-1}, A_{t-1}^{UIP})S_tB_{t-1} + \widetilde{NX}_t, \\ \frac{S_tB_t}{P_{H,t}Y_{H,t}} &= R_{t-1}^*\Psi^B(Z_{t-1}, A_{t-1}^{UIP})\frac{S_{t-1}B_{t-1}S_tP_{H,t-1}Y_{H,t-1}}{P_{H,t-1}Y_{H,t-1}S_{t-1}P_{H,t}Y_{H,t}} + \frac{\widetilde{NX}_t}{P_{H,t}Y_{H,t}}, \\ Z_t &= R_{t-1}^*\Psi^B(Z_{t-1}, A_{t-1}^{UIP})Z_{t-1}\frac{S_tP_{H,t-1}Y_{H,t-1}}{S_{t-1}P_{H,t}Y_{H,t}} + \frac{\widetilde{NX}_t}{P_{H,t}Y_{H,t}},\end{aligned} \tag{B.5.1}$$

where $\widetilde{NX}_t$ are nominal domestic net exports in domestic currency. These are defined as a difference of nominal exports and nominal imports,

$$\widetilde{NX}_t = P_{H,t}C_{H,t}^* - RER_tP_t(C_{F,t} + INV_{F,t}).$$

Law of one price holds for domestic exports, therefore, the price of exports in domestic currency is given by $S_tP_{H,t}^* = S_t\frac{P_{H,t}}{S_t} = P_{H,t}$. Retailers pay only the wholesale price for imports to the foreigners. That is why we use price $RER_tP_t = S_tP_t^*$ for the imports in the nominal net exports definition.

We assume that foreign agents have the same preferences as households, hence we can write the foreign demand for domestic exports as

$$C^*_{H,t} = \gamma \left(\frac{P^*_{H,t}}{P^*_t}\right)^{-\eta} Y^*_t.$$

Since $P^*_{H,t} = \frac{P_{H,t}}{S_t}$ and $\frac{P^*_{H,t}}{P^*_t} = \frac{P_{H,t}}{P_t RER_t}$, we can rewrite the foreign demand for domestic exports in following form,

$$C^*_{H,t} = \gamma \left(\frac{P_{H,t}}{P_t}\right)^{-\eta} \left(\frac{1}{RER_t}\right)^{-\eta} Y^*_t. \tag{B.5.2}$$

Using equation (B.1.8) and its analogue for $INV_{F,t}$ together with equation (B.5.2) we can express the nominal net exports as

$$\widetilde{NX}_t = \gamma P_{H,t} \left(\frac{P_{H,t}}{P_t}\right)^{-\eta} \left(\frac{1}{RER_t}\right)^{-\eta} Y^*_t - \gamma RER_t P_t \left(\frac{P_{F,t}}{P_t}\right)^{-\eta} (C_t + INV_t). \tag{B.5.3}$$

Now, we return to the law of motion of net foreign assets position (B.5.1) and plug in the nominal net exports from equation (B.5.3). Since foreign bonds and consequently also net foreign assets position are both assumed to be equal to zero in steady state ($\overline{B} = 0$, $\overline{Z} = 0$) we will linearize the terms containing Z_t and Z_{t-1} and log-linearize the rest to obtain

$$\begin{aligned} z_t = \overline{R}^* \Psi^B(\overline{Z}, \overline{A^{UIP}}) z_{t-1} + \gamma \Big[&(1-\eta) p_{H,t} - p_t + \eta p_{F,t} + (\eta - 1) rer_t + \\ &+ y^*_t - \frac{\overline{C}}{\overline{Y}_H} c_t - \frac{\overline{INV}}{\overline{Y}_H} inv_t \Big], \end{aligned}$$

where we use the assumption $\overline{R}^* \Psi^B(\overline{Z}, \overline{A}^{UIP}) = \overline{R} = \frac{1}{\beta}$, relations (3.1.9) and (3.1.11) and after some algebra we obtain

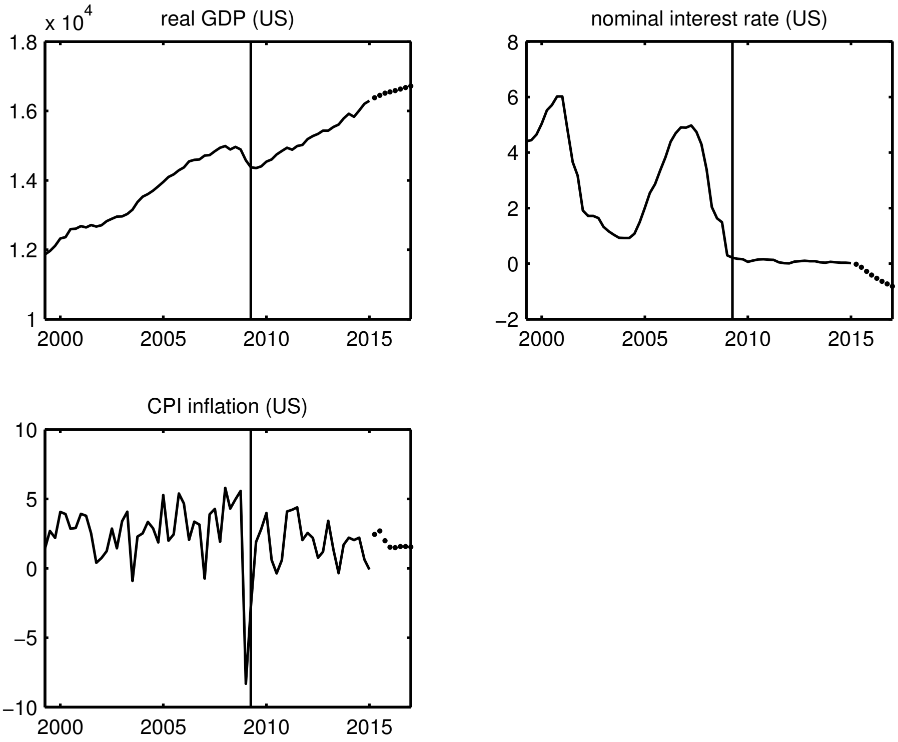
$$z_t = \frac{1}{\beta} z_{t-1} + \gamma y^*_t + \gamma \frac{2\eta - \gamma\eta - 1}{1-\gamma} rer_t + \frac{\gamma - \eta}{1-\gamma} lop_t - \gamma \frac{\overline{C}}{\overline{Y}_H} c_t - \gamma \frac{\overline{INV}}{\overline{Y}_H} inv_t. \tag{B.5.4}$$

Appendix C

Figures

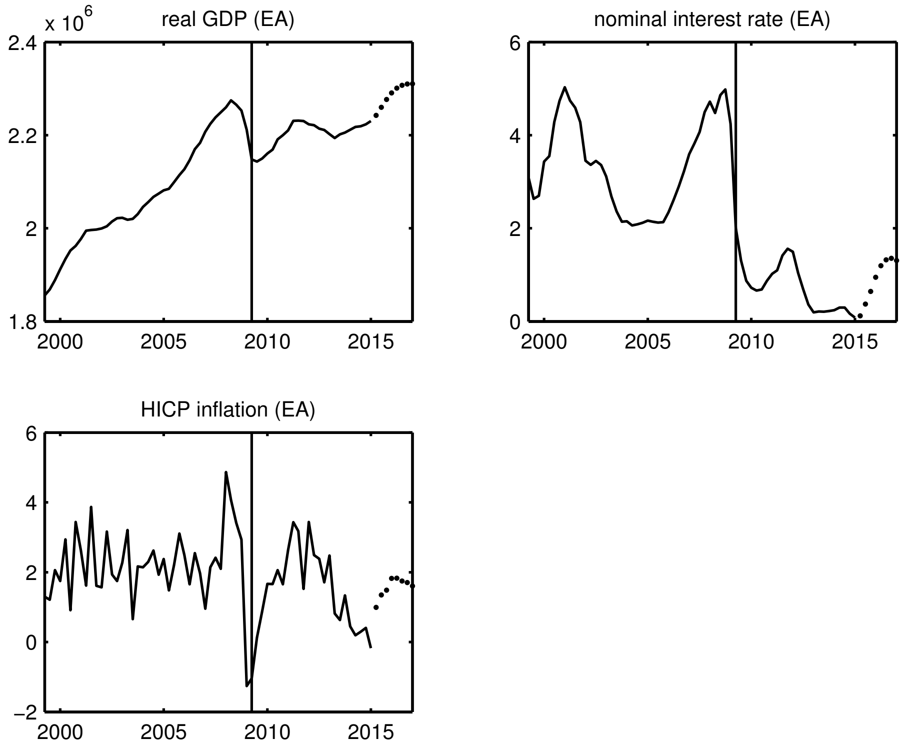
C.1 Data

Figure C.1: U.S. foreign block, VAR forecast



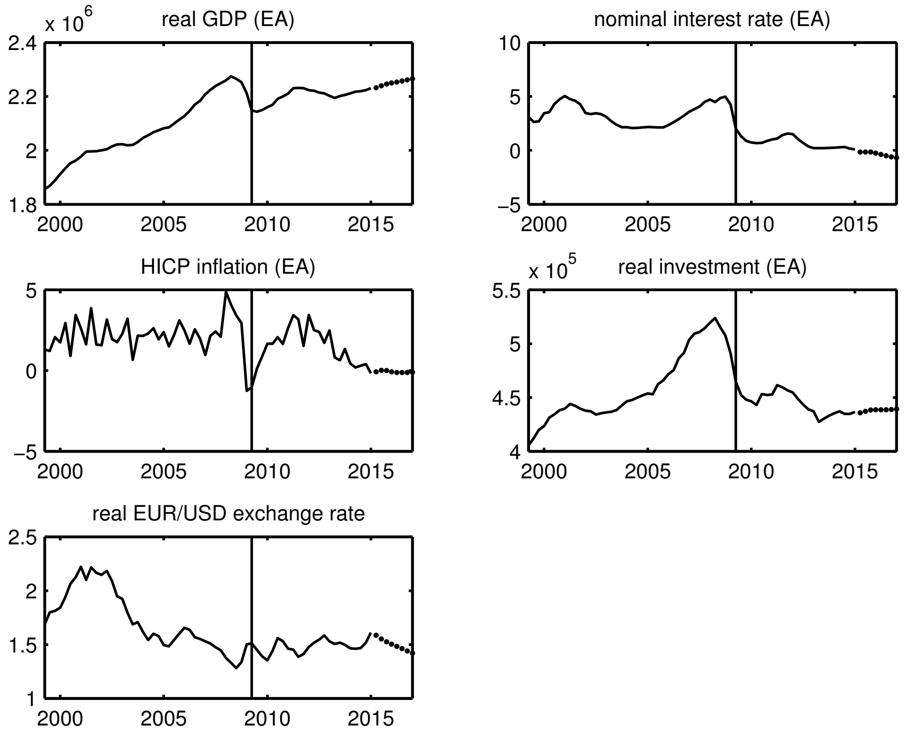
Source: Author, Data: St. Louis FRED.
Note: Solid line - observed data, dotted line - unconditional VAR forecast, vertical line - 2009Q1.

Figure C.2: EA foreign block, VAR forecast



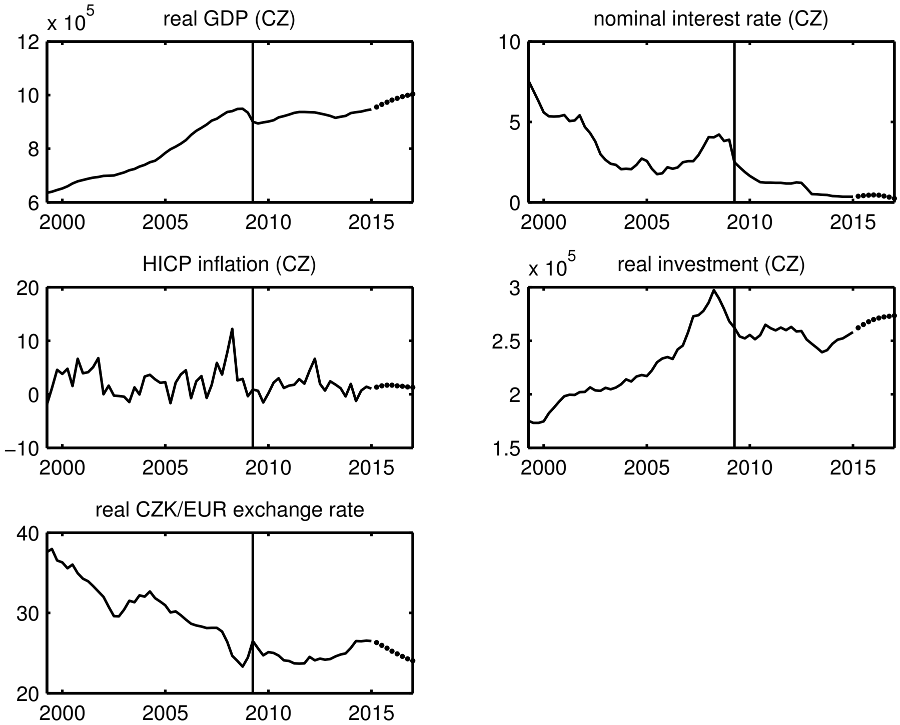
Source: Author, Data: Eurostat.
Note: Solid line - observed data, dotted line - unconditional VAR forecast, vertical line - 2009Q1.

Figure C.3: EA domestic block, VAR forecast



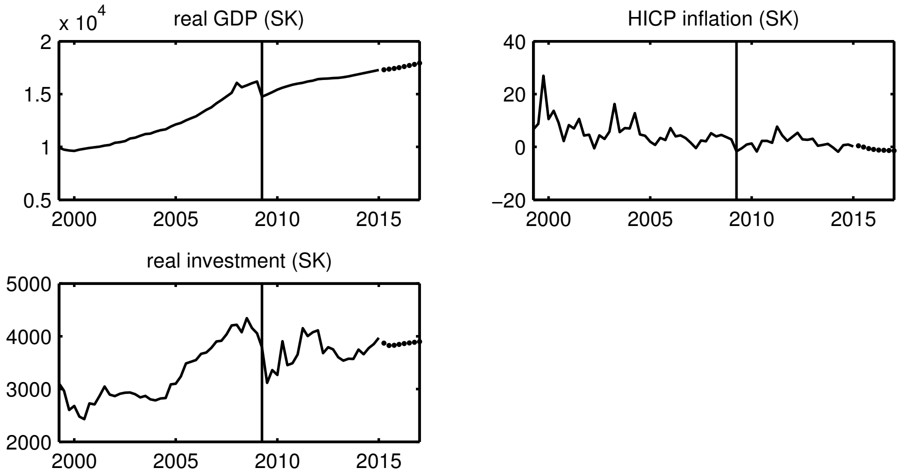
Source: Author, Data: Eurostat, ECB.
Note: Solid line - observed data, dotted line - conditional VAR forecast, vertical line - 2009Q1.

Figure C.4: CZ domestic block, VAR forecast



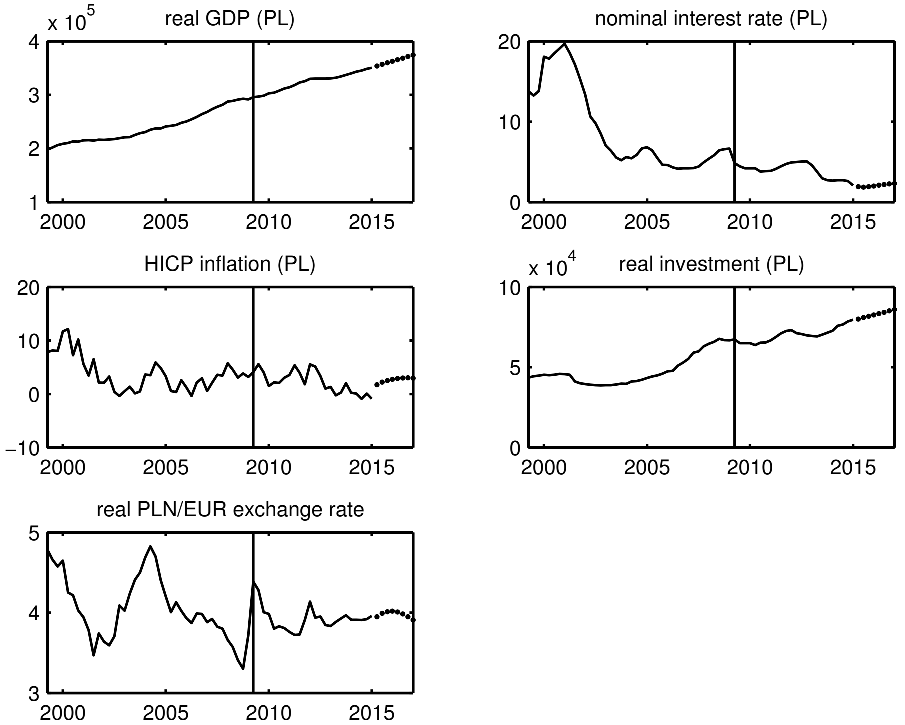
Source: Author, Data: Eurostat, ECB, CNB.
Note: Solid line - observed data, dotted line - conditional VAR forecast, vertical line - 2009Q1.

Figure C.5: SK domestic block, VAR forecast



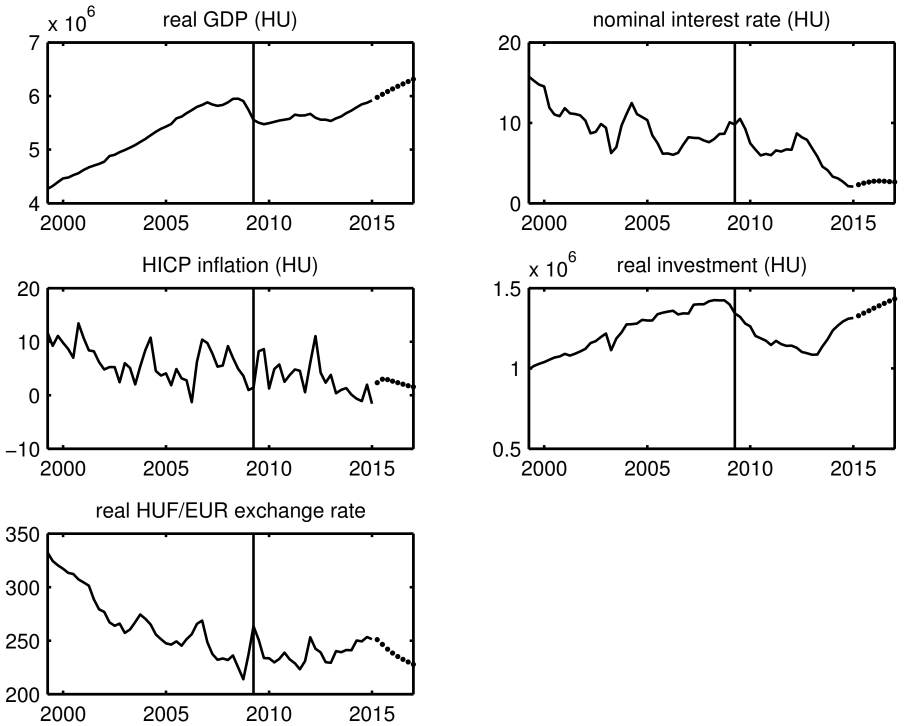
Source: Author, Data: Eurostat, ECB, NBS.
Note: Solid line - observed data, dotted line - conditional VAR forecast, vertical line - 2009Q1.

Figure C.6: PL domestic block, VAR forecast



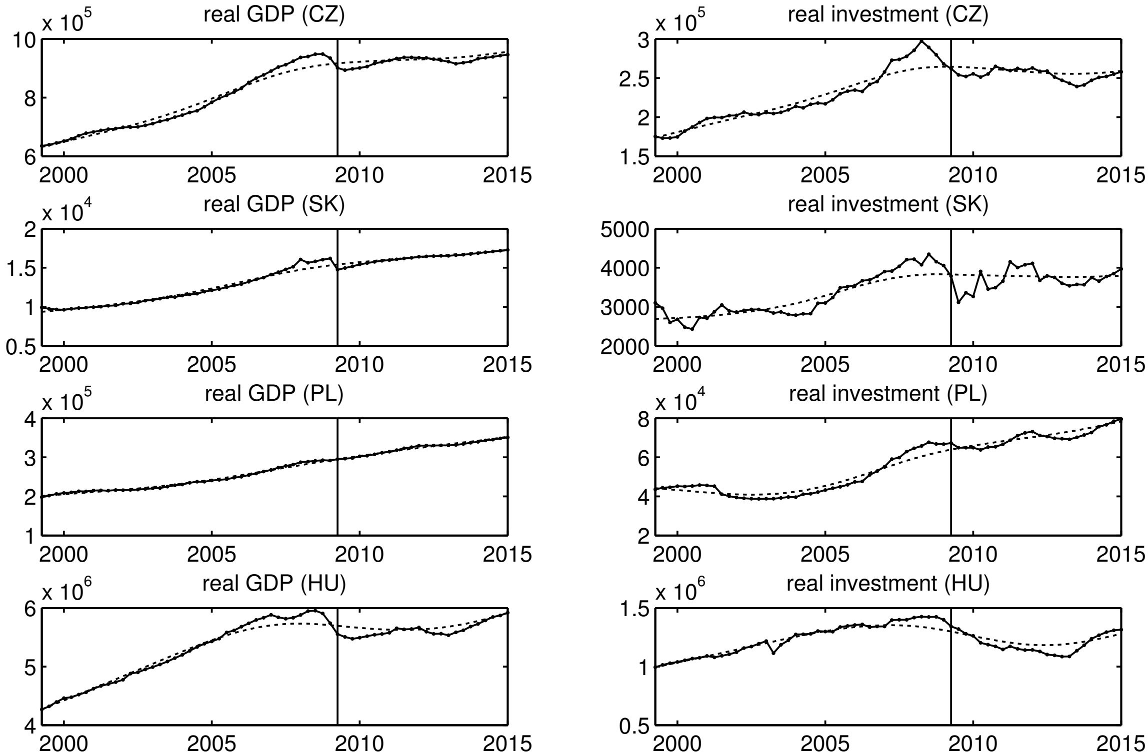
Source: Author, Data: Eurostat, ECB, NBP.
Note: Solid line - observed data, dotted line - conditional VAR forecast, vertical line - 2009Q1.

Figure C.7: HU domestic block, VAR forecast



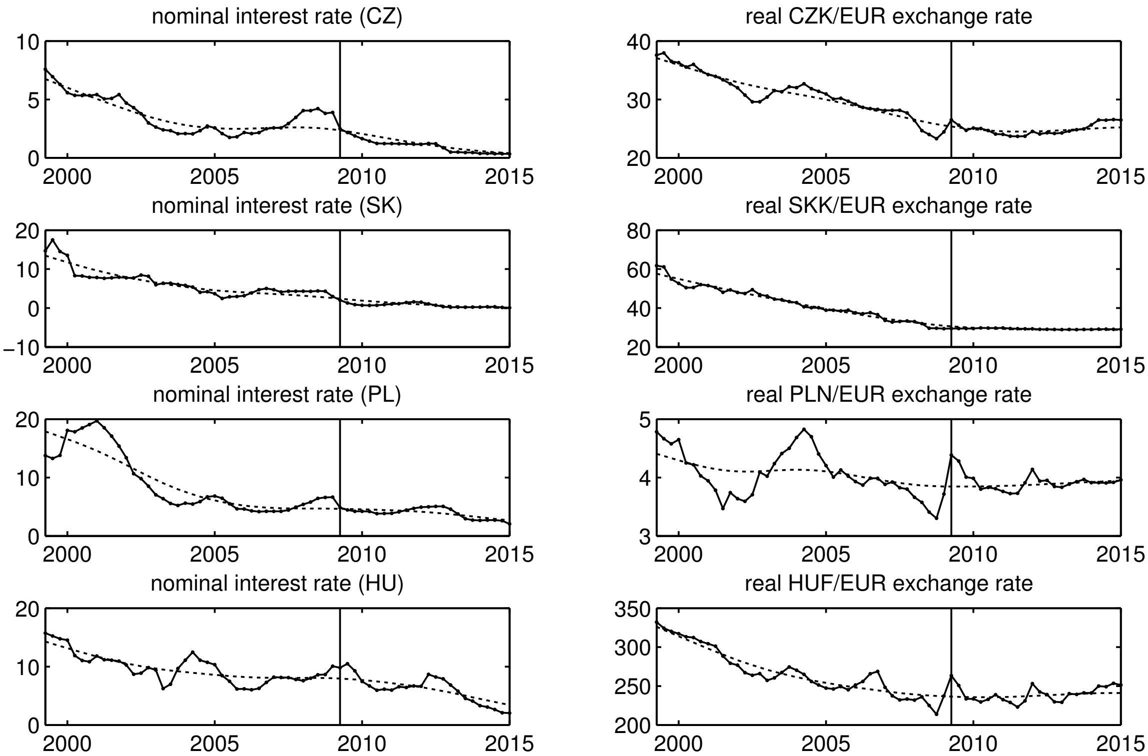
Source: Author, Data: Eurostat, ECB, MNB.
Note: Solid line - observed data, dotted line - conditional VAR forecast, vertical line - 2009Q1.

Figure C.8: Input data with HP trend (1 of 4)



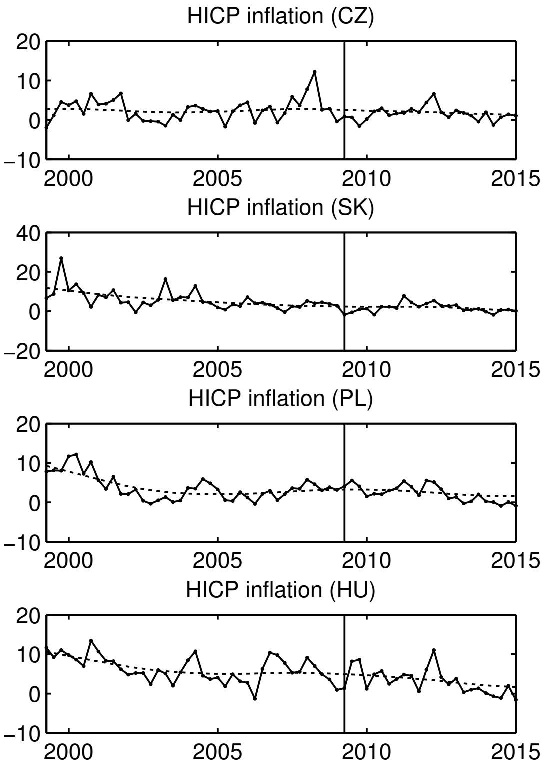
Source: Author, Data: Eurostat.
Note: Solid line - observed data, dotted line - HP trend, vertical line - 2009Q1.

Figure C.9: Input data with HP trend (2 of 4)



Source: Author, Data: ECB, CNB, NBS, NBP, MNB.
Note: Solid line - observed data, dotted line - HP trend, vertical line - 2009Q1.

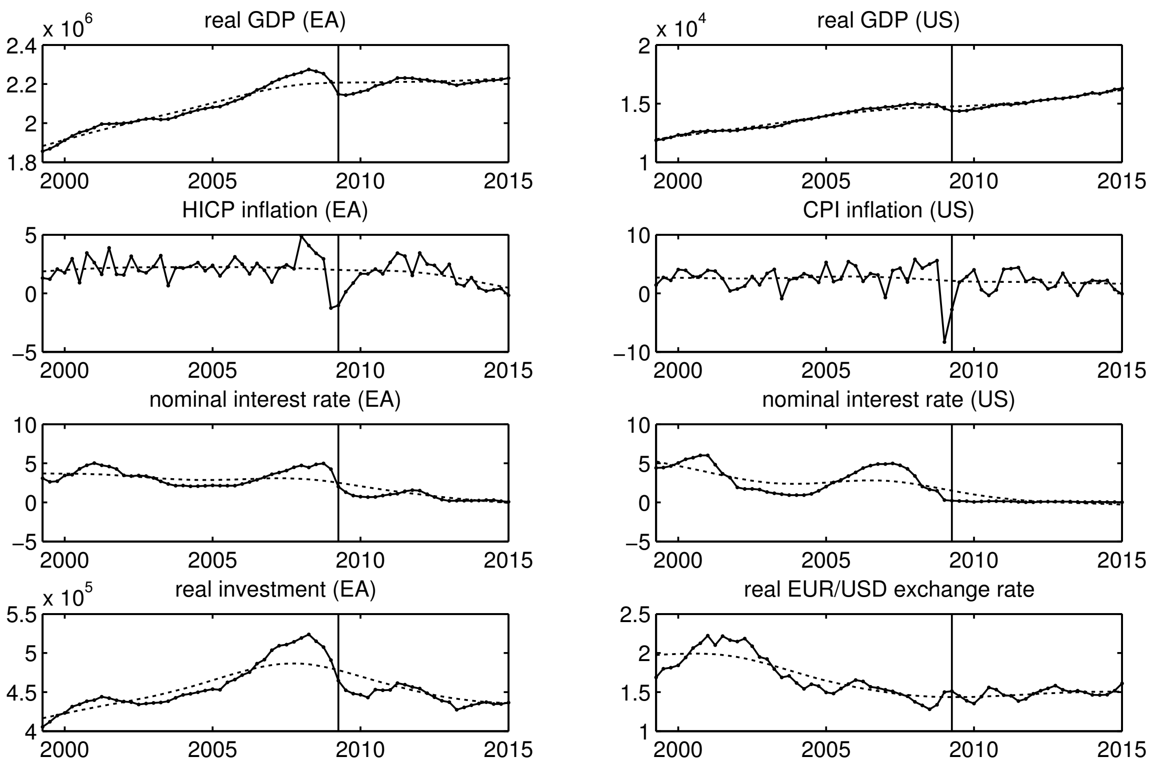
Figure C.10: Input data with HP trend (3 of 4)



Source: Author, Data: Eurostat.

Note: Solid line - observed data, dotted line - HP trend, vertical line - 2009Q1.

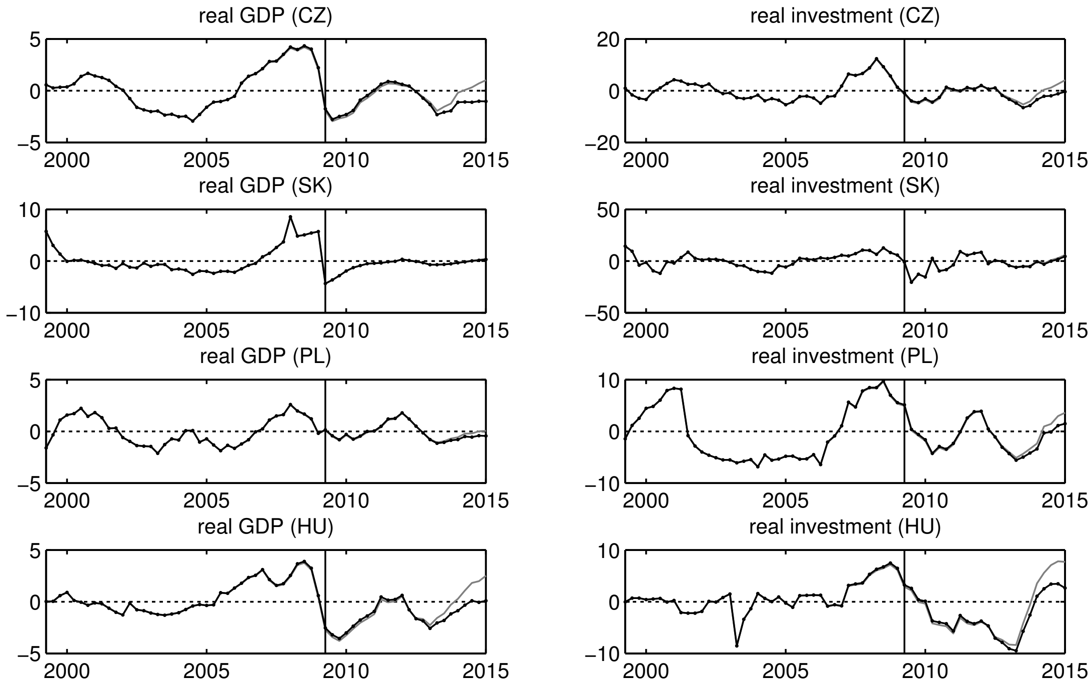
Figure C.11: Input data with HP trend (4 of 4)



Source: Author, Data: St. Louis FRED, Eurostat, ECB.

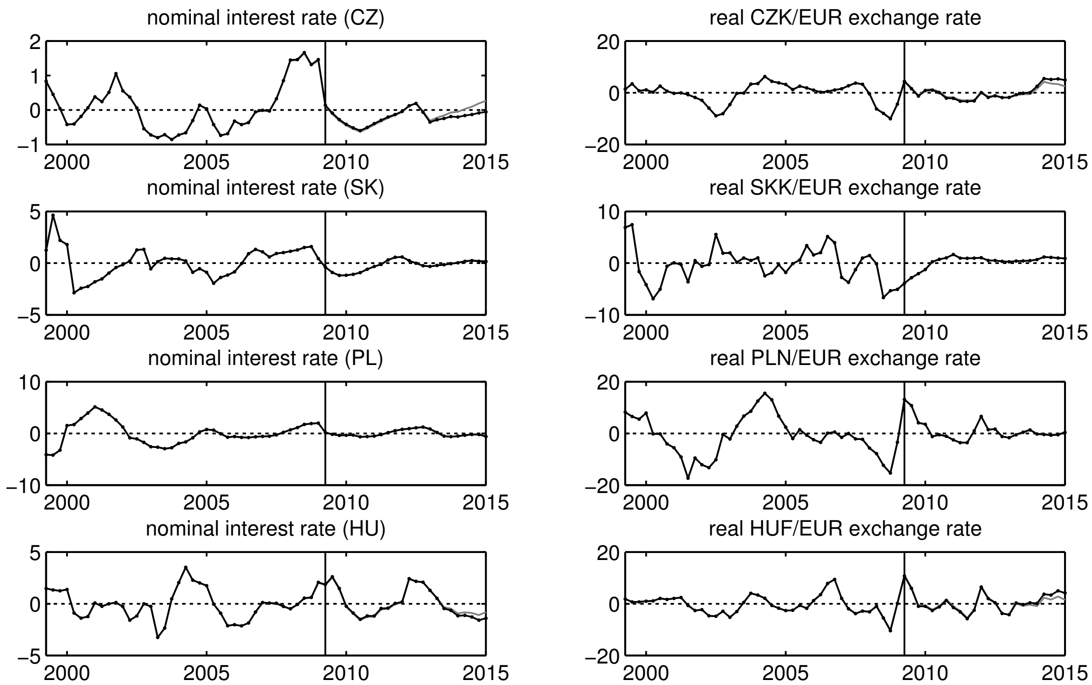
Note: Solid line - observed data, dotted line - HP trend, vertical line - 2009Q1.

Figure C.12: End-of-sample bias correction using VAR forecast (1 of 4)



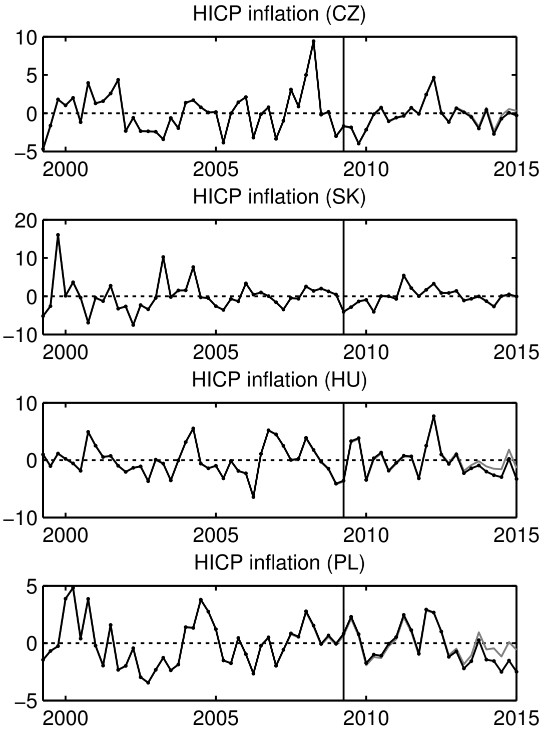
Source: Author, Data: Eurostat.
Note: Per cent deviations from steady state are depicted, black line - data extended with VAR forecast, gray line - observed data only, vertical line - 2009Q1.

Figure C.13: End-of-sample bias correction using VAR forecast (2 of 4)



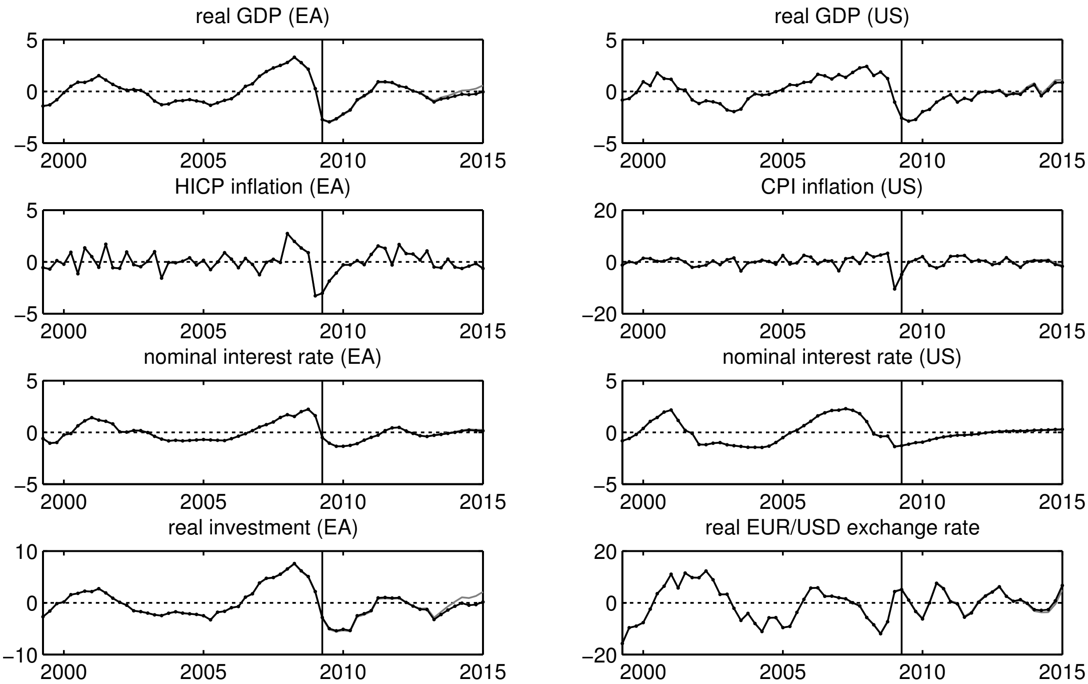
Source: Author, Data: ECB, CNB, NBS, NBP, MNB.
Note: Per cent deviations from steady state are depicted, black line - data extended with VAR forecast, gray line - observed data only, vertical line - 2009Q1.

Figure C.14: End-of-sample bias correction using VAR forecast (3 of 4)



Source: Author, Data: Eurostat.
Note: Per cent deviations from steady state are depicted, black line - data extended with VAR forecast, gray line - observed data only, vertical line - 2009Q1.

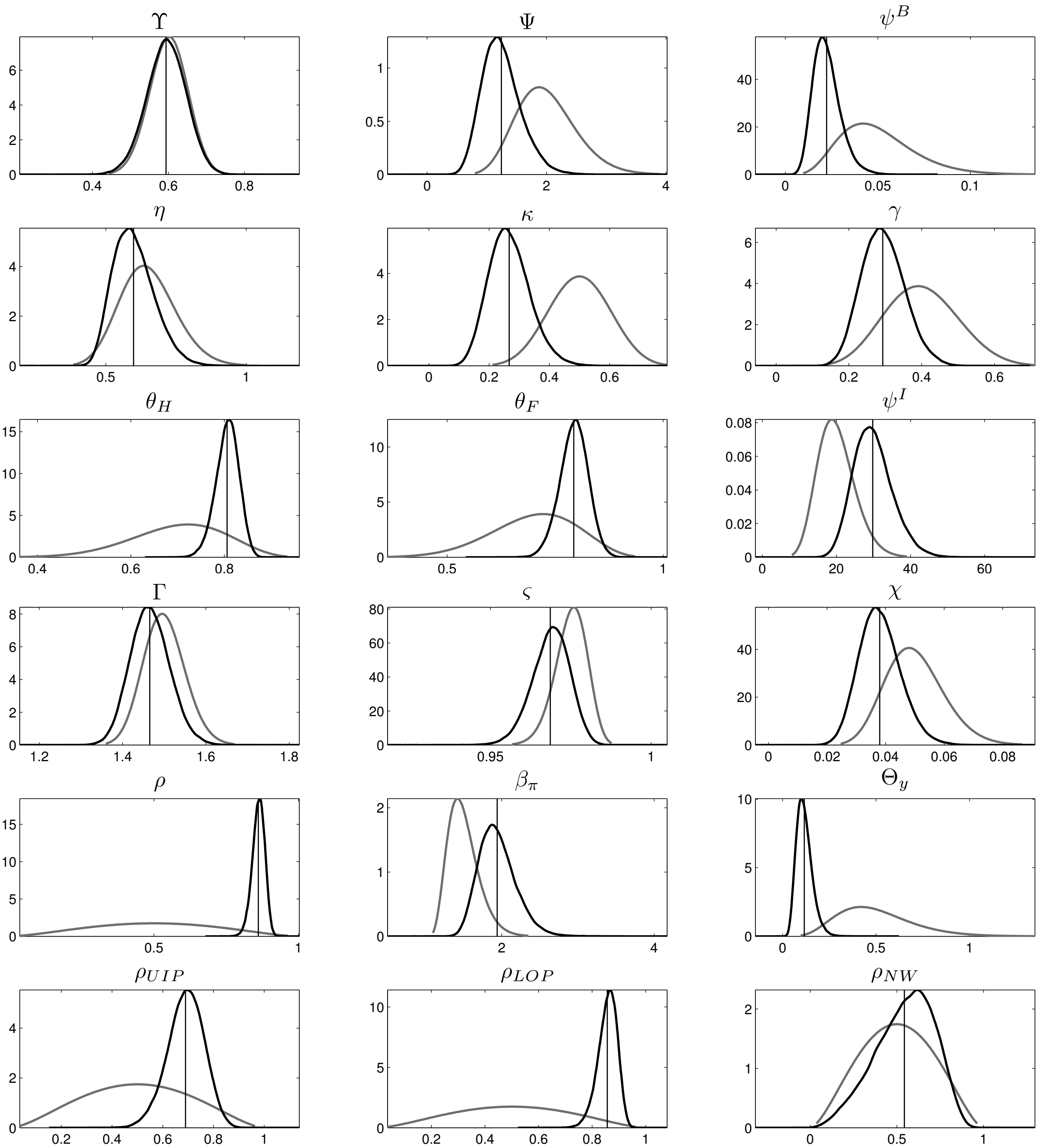
Figure C.15: End-of-sample bias correction using VAR forecast (4 of 4)



Source: Author, Data: St. Louis FRED, Eurostat, ECB.
Note: Per cent deviations from steady state are depicted, black line - data extended with VAR forecast, gray line - observed data only, vertical line - 2009Q1.

C.2 Prior and posterior distributions

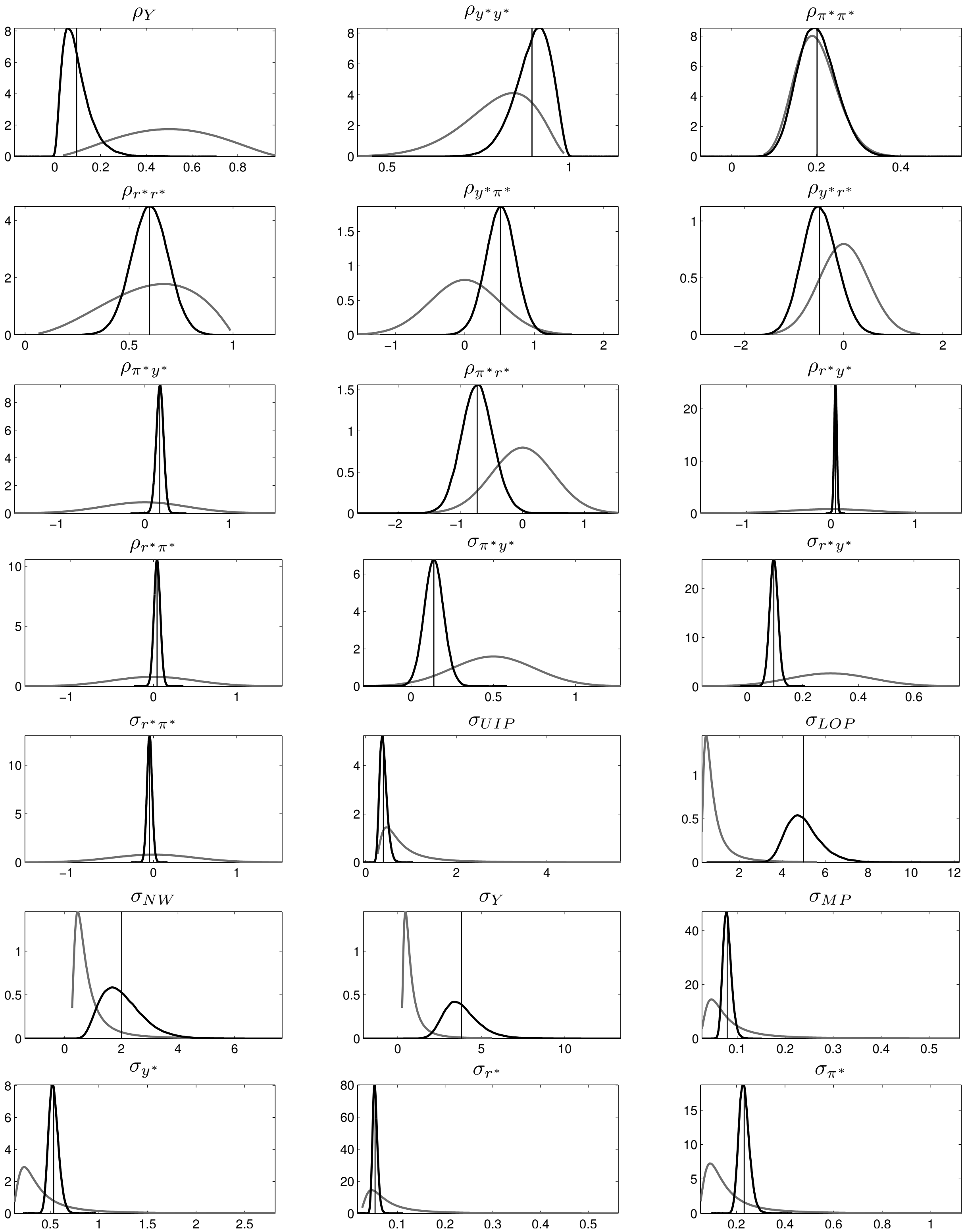
Figure C.16: Prior and posterior distribution of CZ model parameters (1 of 2)



Source: Author.

Note: Grey line - prior density, black line - posterior density, vertical line - posterior mode.

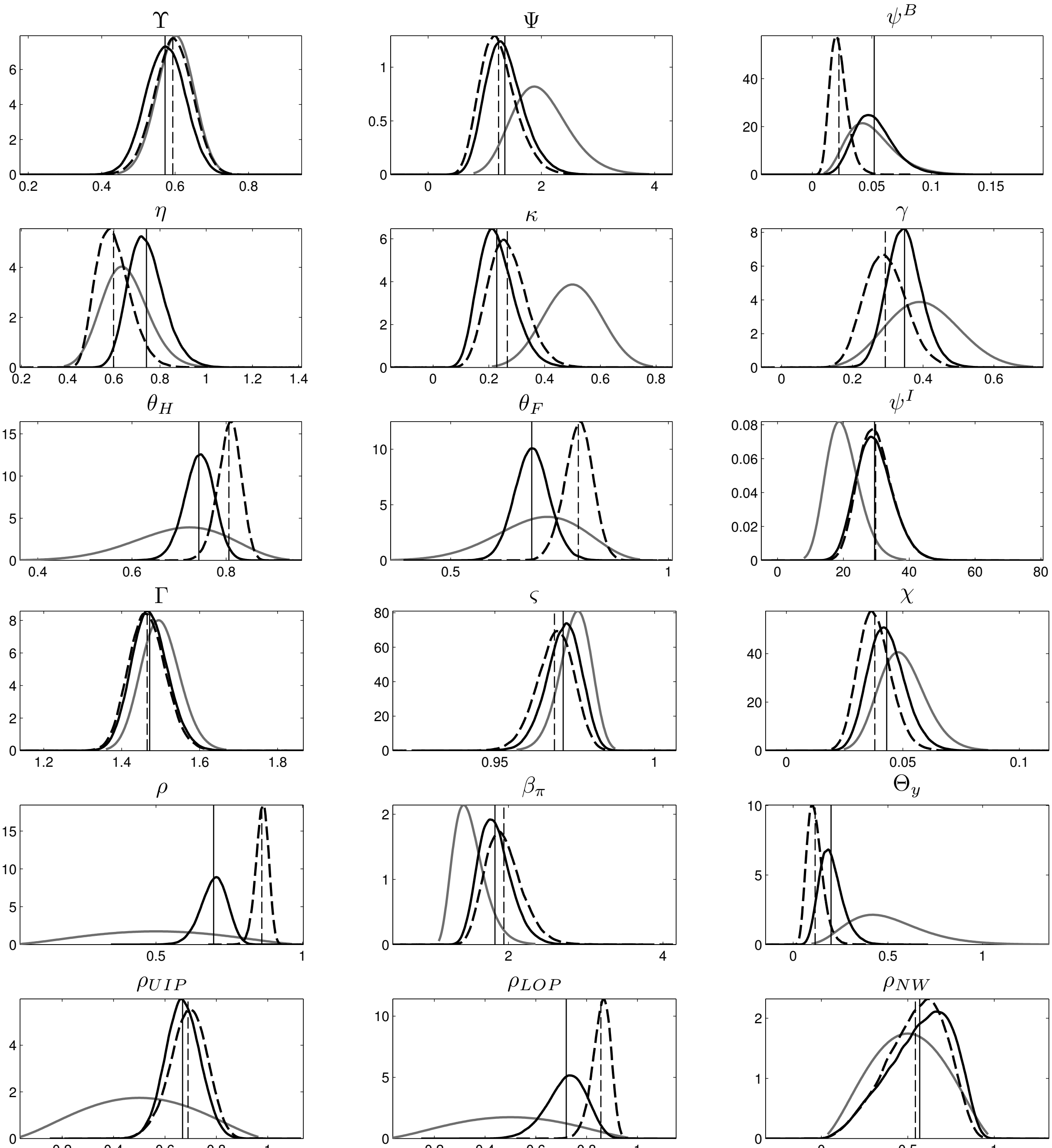
Figure C.17: Prior and posterior distribution of CZ model parameters (2 of 2)



Source: Author.

Note: Grey line - prior density, black line - posterior density, vertical line - posterior mode.

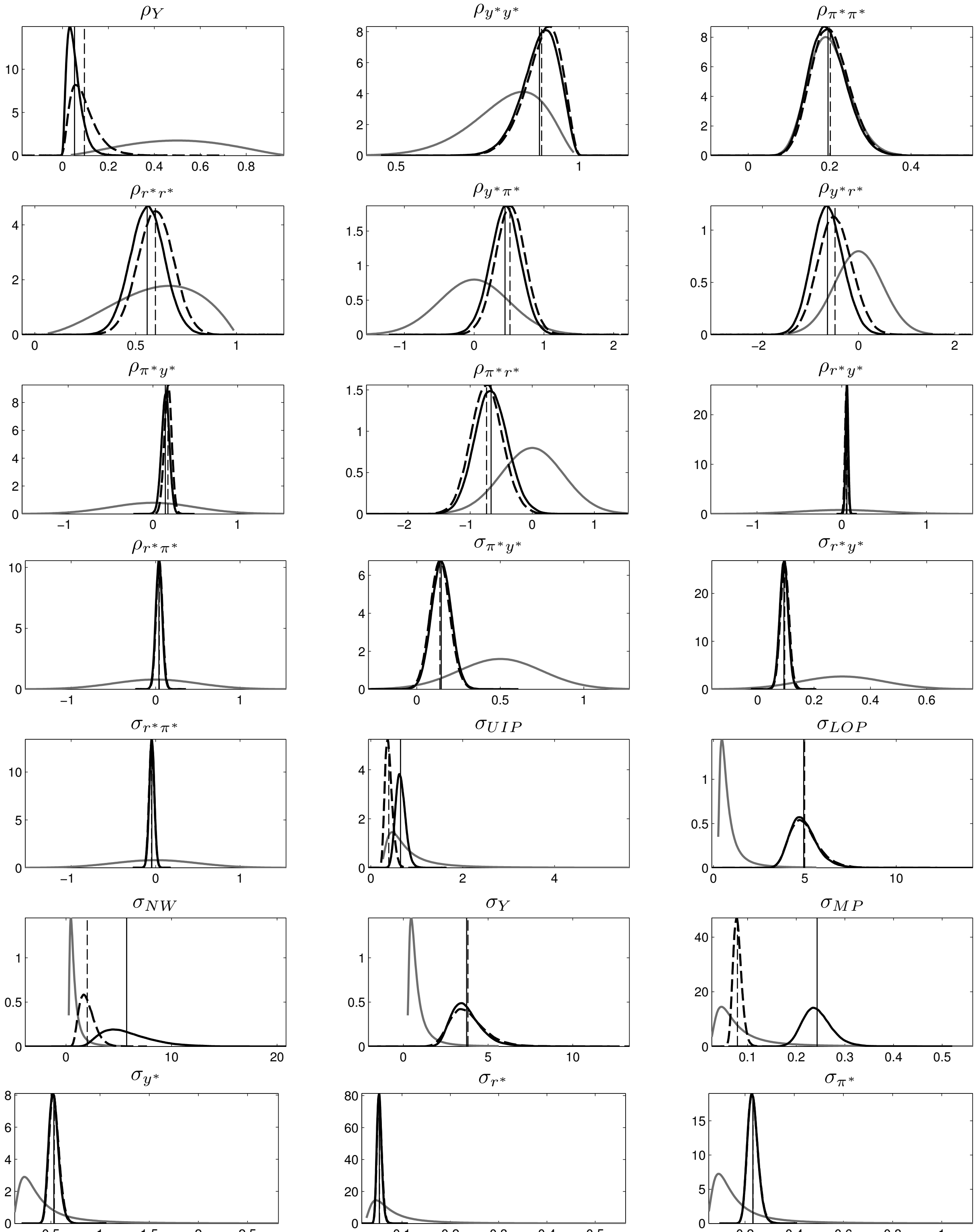
Figure C.18: Prior and posterior distribution of SK model parameters (1 of 2)



Source: Author.

Note: Grey line - prior density, black line - posterior density, vertical line - posterior mode, dashed line - CZ posterior density, dashed vertical line - CZ posterior mode.

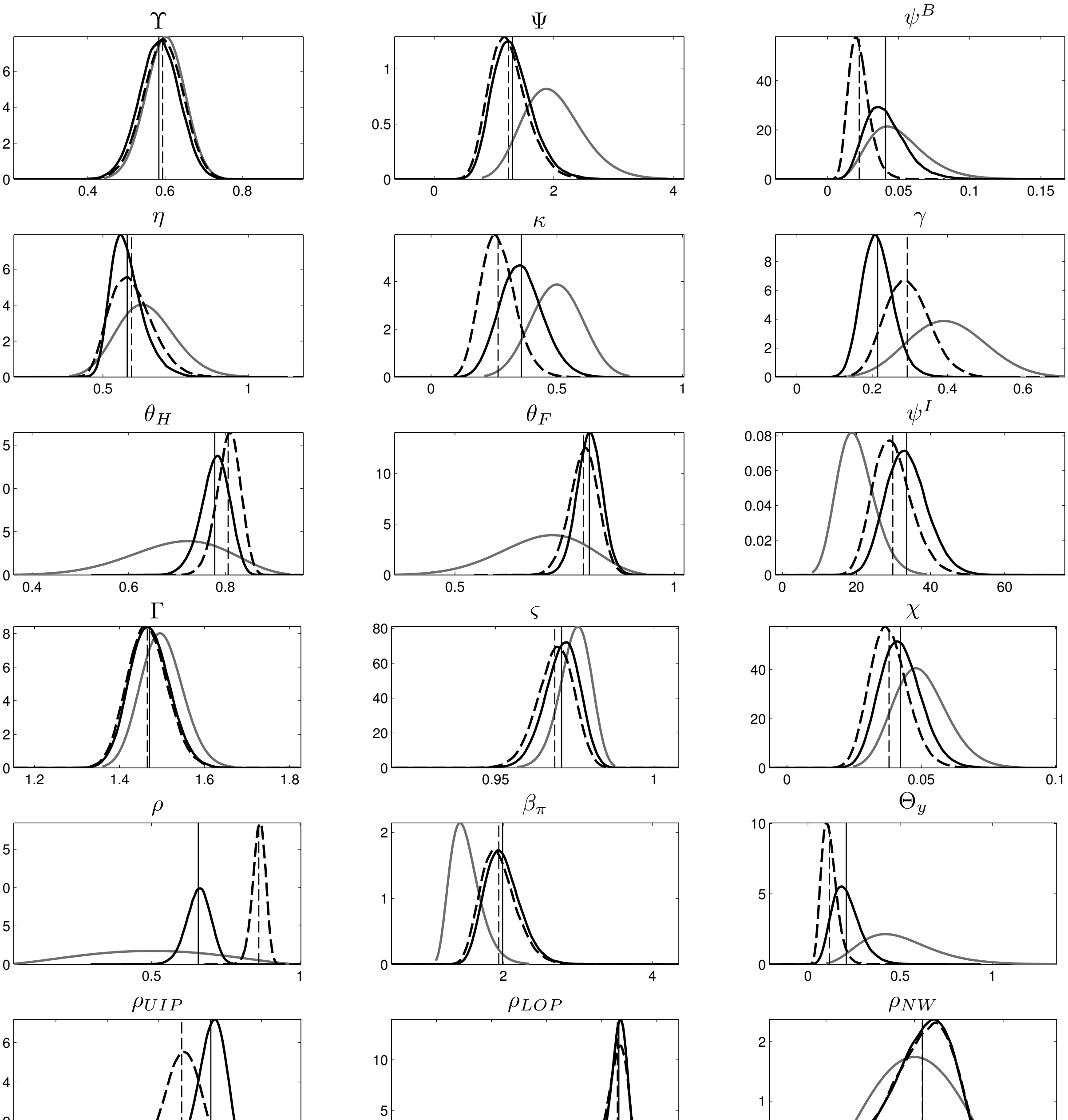
Figure C.19: Prior and posterior distribution of SK model parameters (2 of 2)



Source: Author.

Note: Grey line - prior density, black line - posterior density, vertical line - posterior mode, dashed line - CZ posterior density, dashed vertical line - CZ posterior mode.

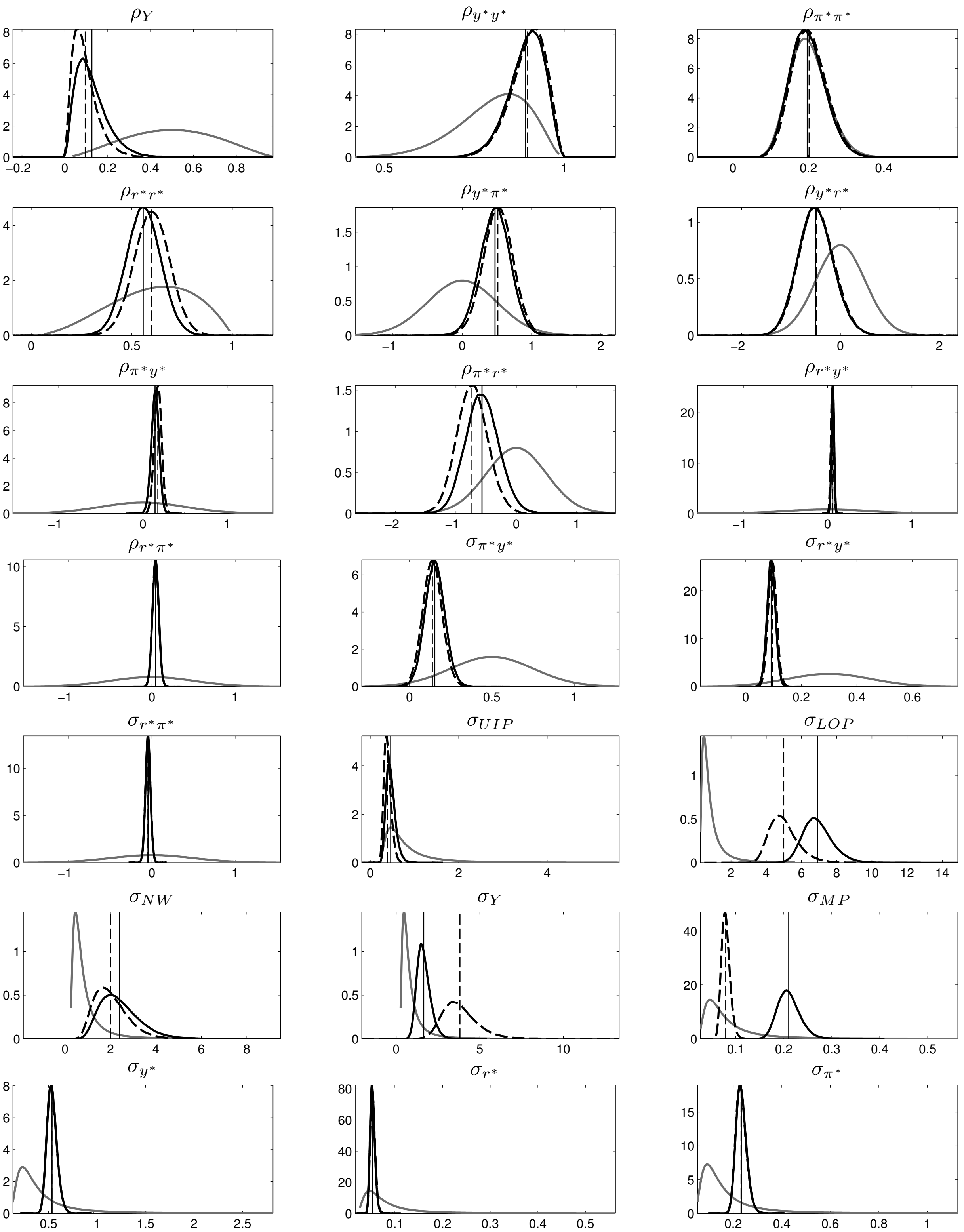
Figure C.20: Prior and posterior distribution of PL model parameters (1 of 2)



Source: Author.

Note: Grey line - prior density, black line - posterior density, vertical line - posterior mode, dashed line - CZ posterior density, dashed vertical line - CZ posterior mode.

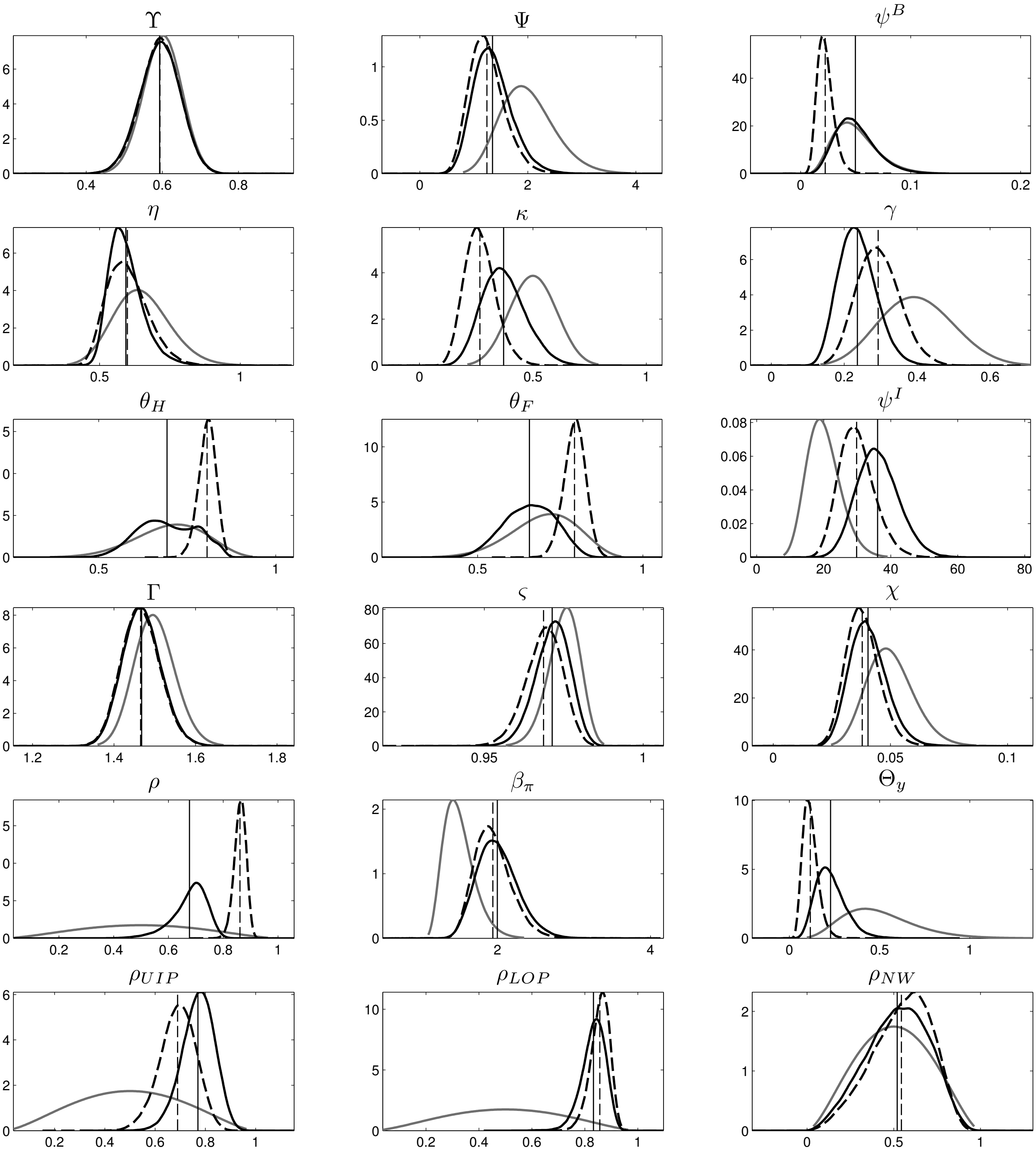
Figure C.21: Prior and posterior distribution of PL model parameters (2 of 2)



Source: Author.

Note: Grey line - prior density, black line - posterior density, vertical line - posterior mode, dashed line - CZ posterior density, dashed vertical line - CZ posterior mode.

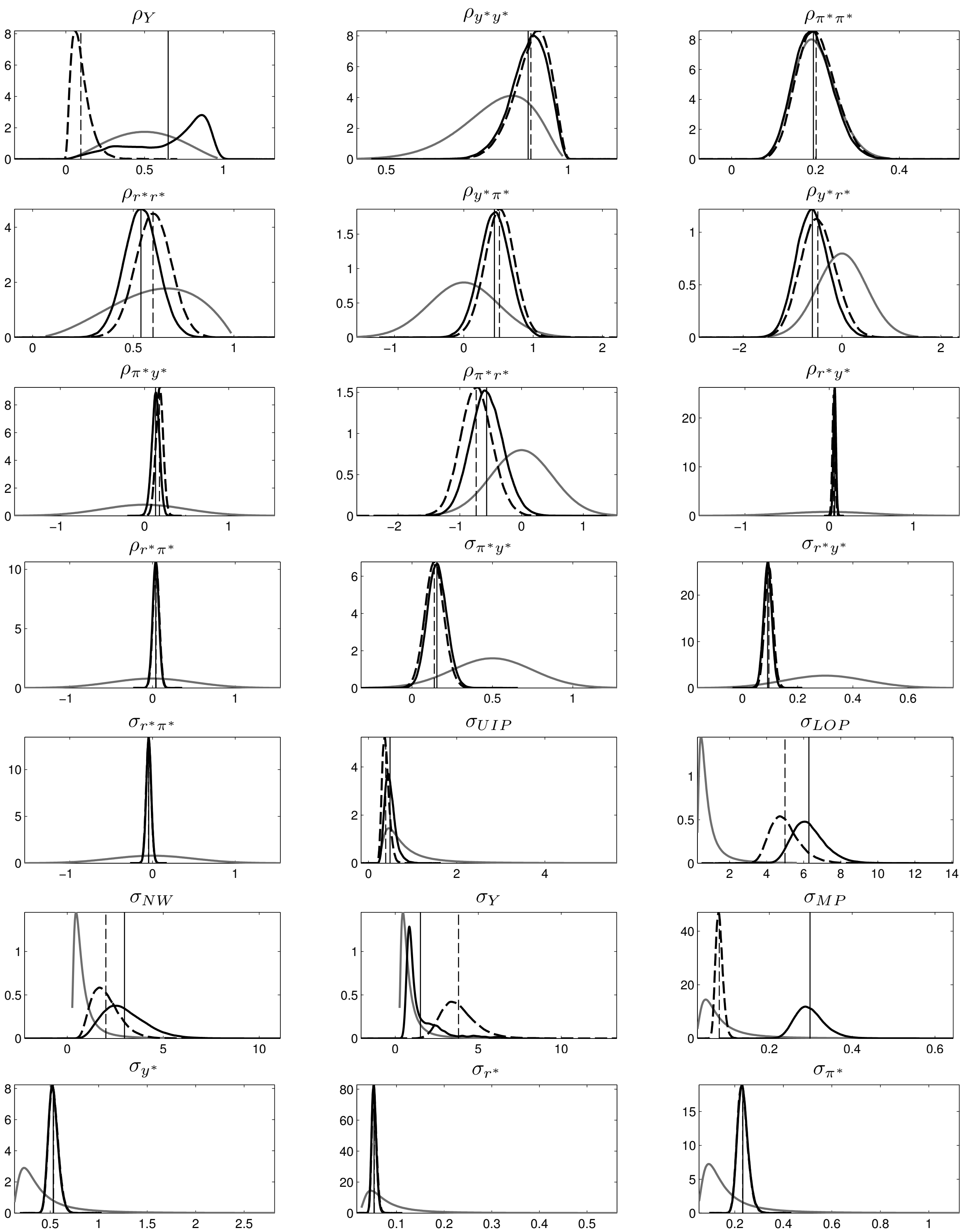
Figure C.22: Prior and posterior distribution of HU model parameters (1 of 2)



Source: Author.

Note: Grey line - prior density, black line - posterior density, vertical line - posterior mode, dashed line - CZ posterior density, dashed vertical line - CZ posterior mode.

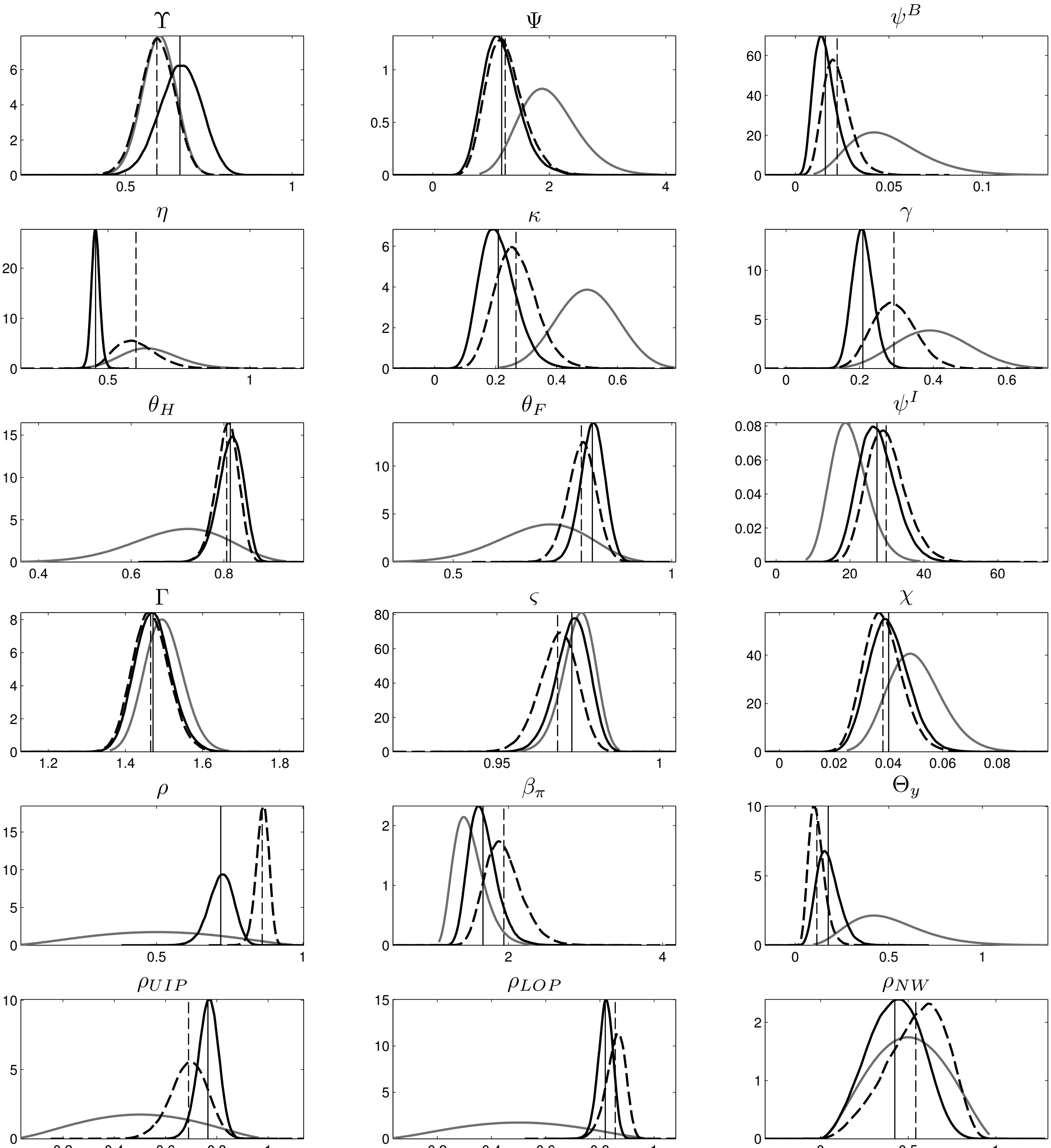
Figure C.23: Prior and posterior distribution of HU model parameters (2 of 2)



Source: Author.

Note: Grey line - prior density, black line - posterior density, vertical line - posterior mode, dashed line - CZ posterior density, dashed vertical line - CZ posterior mode.

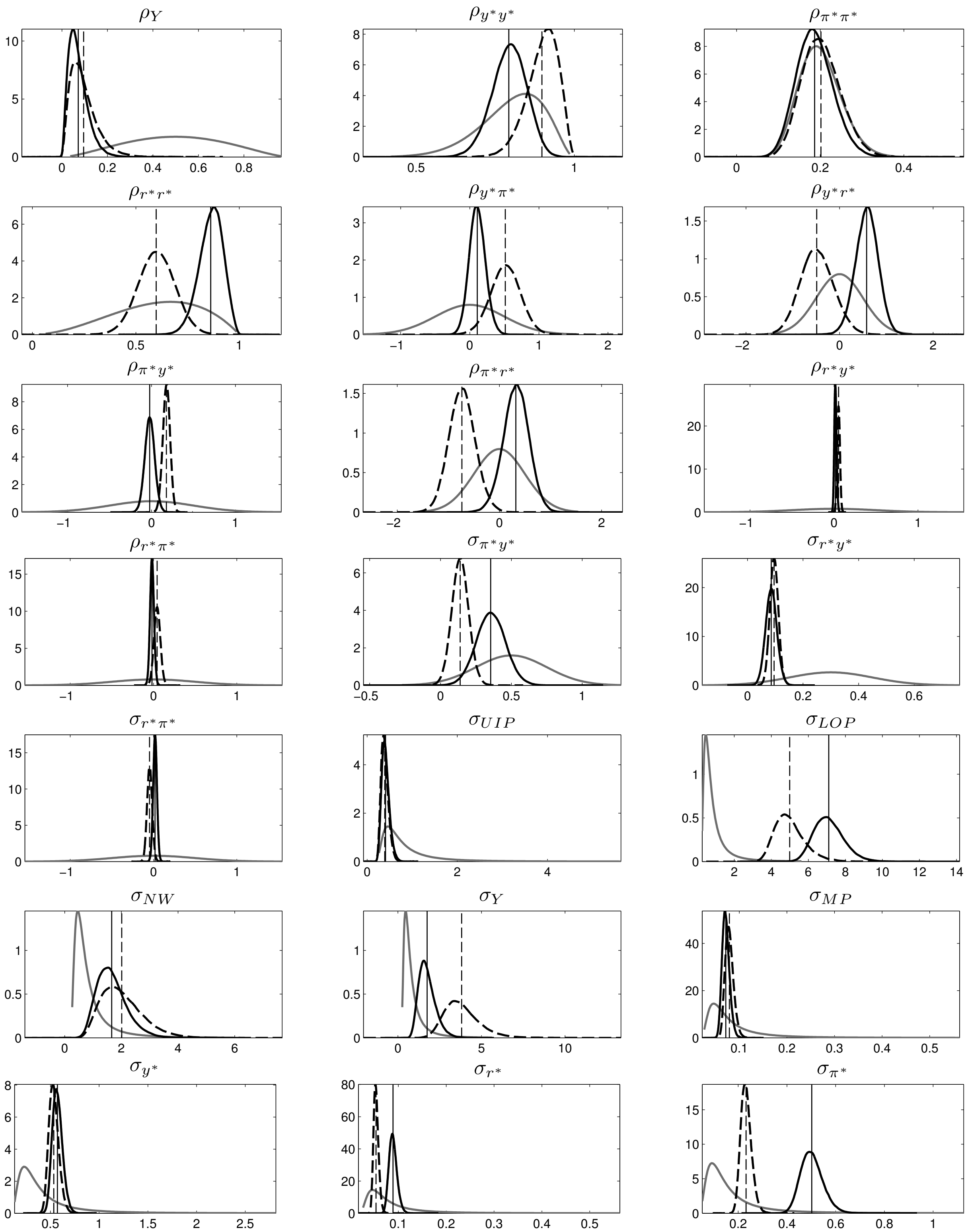
Figure C.24: Prior and posterior distribution of EA model parameters (1 of 2)



Source: Author.

Note: Grey line - prior density, black line - posterior density, vertical line - posterior mode, dashed line - CZ posterior density, dashed vertical line - CZ posterior mode.

Figure C.25: Prior and posterior distribution of EA model parameters (2 of 2)

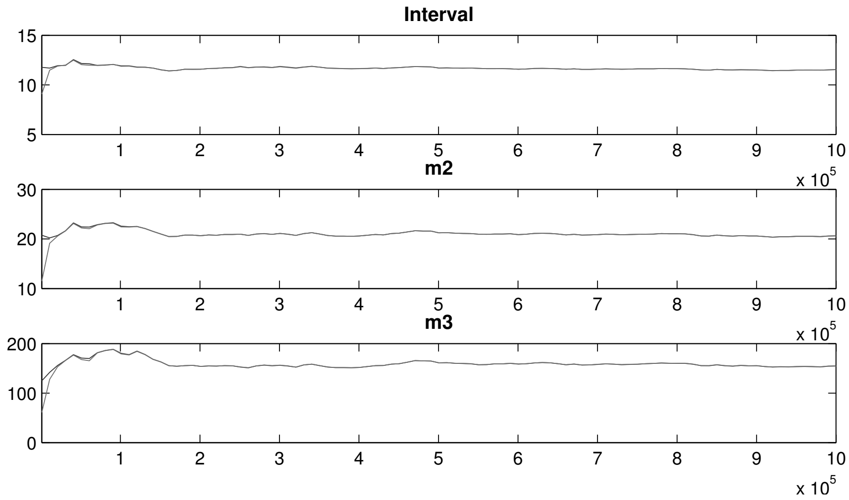


Source: Author.

Note: Grey line - prior density, black line - posterior density, vertical line - posterior mode, dashed line - CZ posterior density, dashed vertical line - CZ posterior mode.

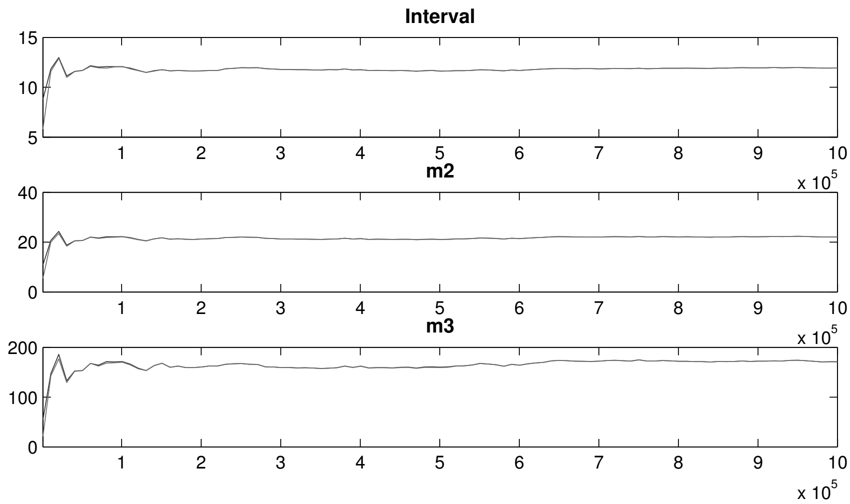
C.3 Convergence diagnostics

Figure C.26: Brooks and Gelman multivariate convergence diagnostics, CZ



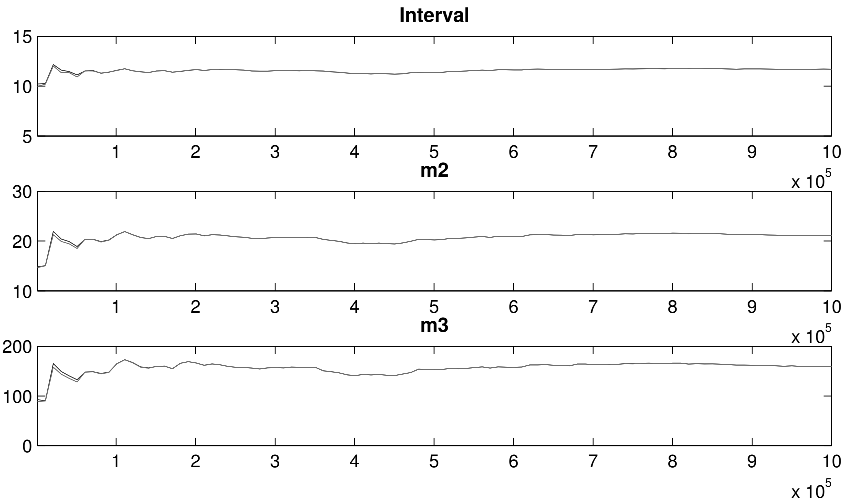
Source: Author.

Figure C.27: Brooks and Gelman multivariate convergence diagnostics, SK



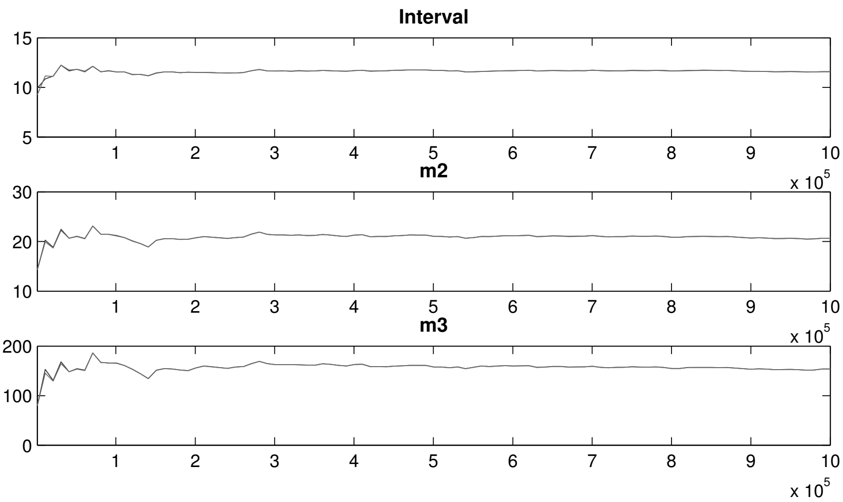
Source: Author.

Figure C.28: Brooks and Gelman multivariate convergence diagnostics, PL



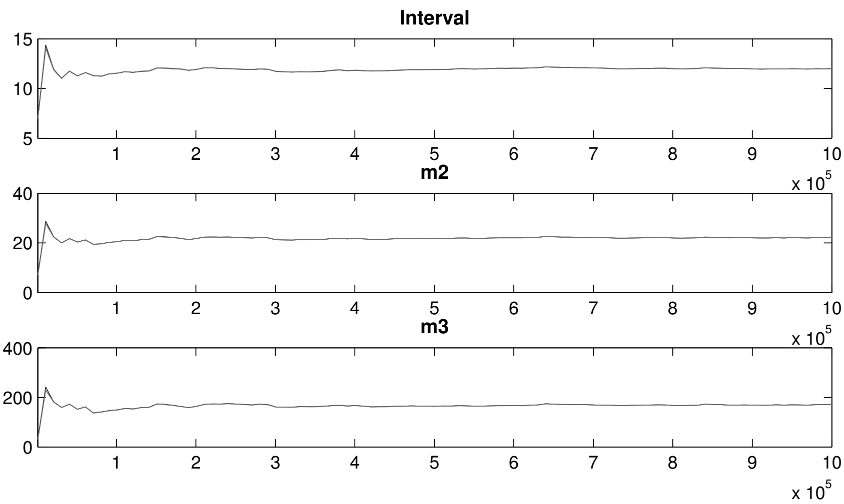
Source: Author.

Figure C.29: Brooks and Gelman multivariate convergence diagnostics, HU



Source: Author.

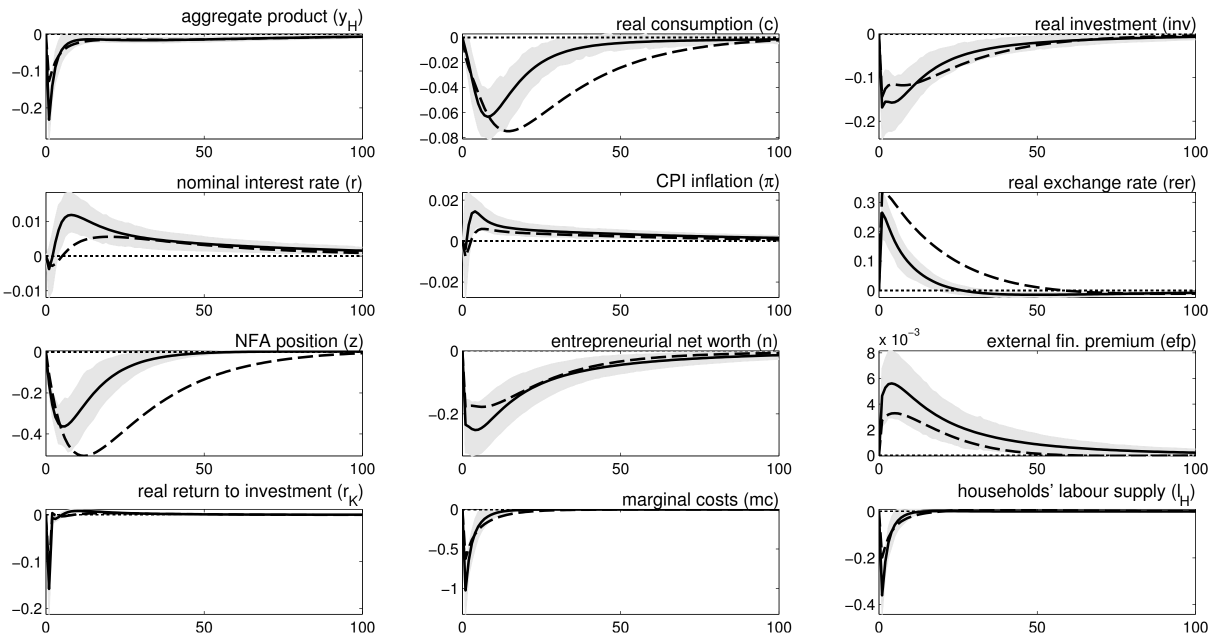
Figure C.30: Brooks and Gelman multivariate convergence diagnostics, EA



Source: Author.

C.4 Impulse response functions

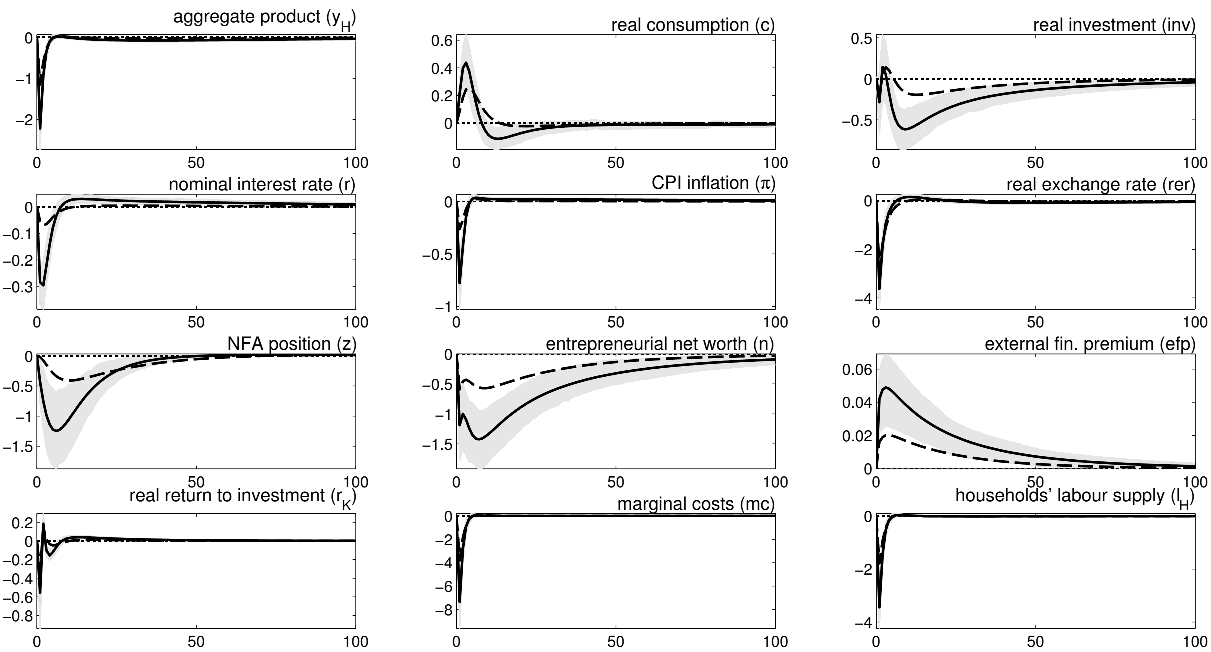
Figure C.31: Impulse responses to law of one price gap shock, SK



Source: Author.

Note: Per cent deviations caused by 1% shock are depicted, solid line - SK, dashed line - CZ.

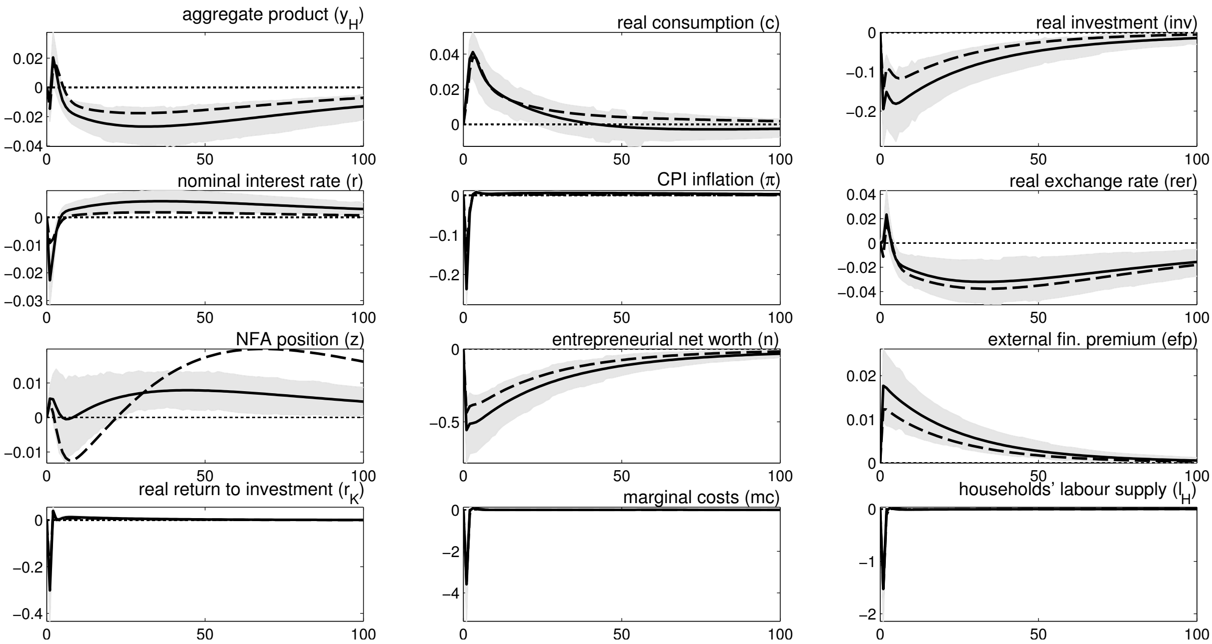
Figure C.32: Impulse responses to debt-elastic risk premium shock, SK



Source: Author.

Note: Per cent deviations caused by 1% shock are depicted, solid line - SK, dashed line - CZ.

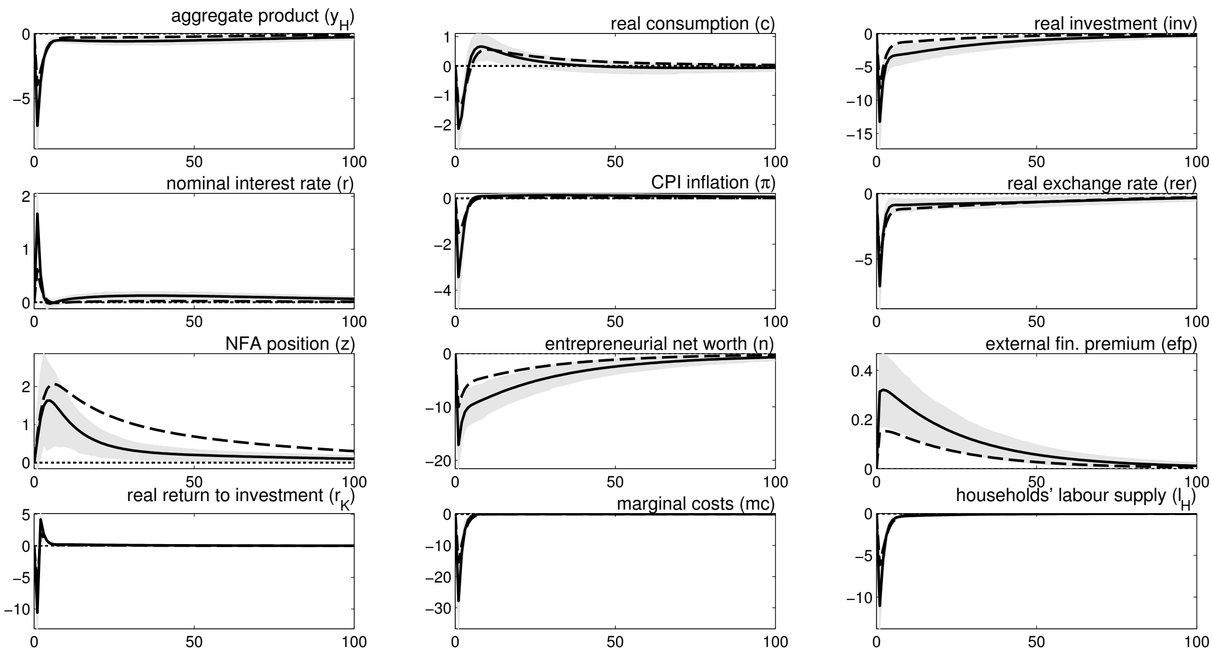
Figure C.33: Impulse responses to productivity shock, SK



Source: Author.

Note: Per cent deviations caused by 1% shock are depicted, solid line - SK, dashed line - CZ.

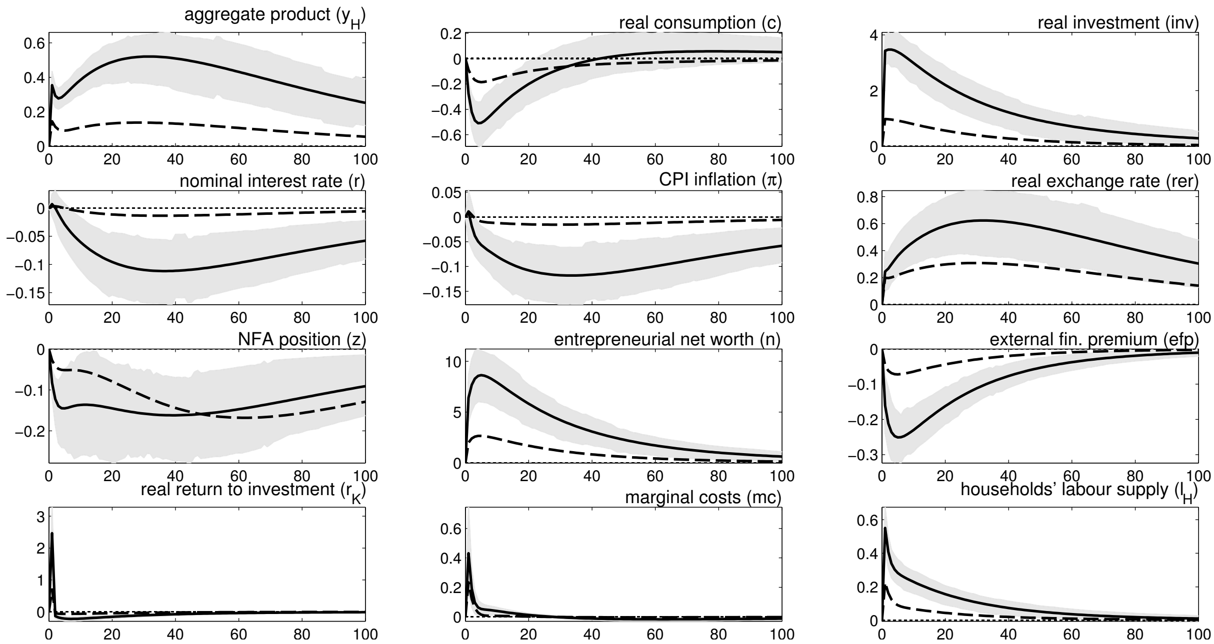
Figure C.34: Impulse responses to monetary policy shock, SK



Source: Author.

Note: Per cent deviations caused by 1% shock are depicted, solid line - SK, dashed line - CZ.

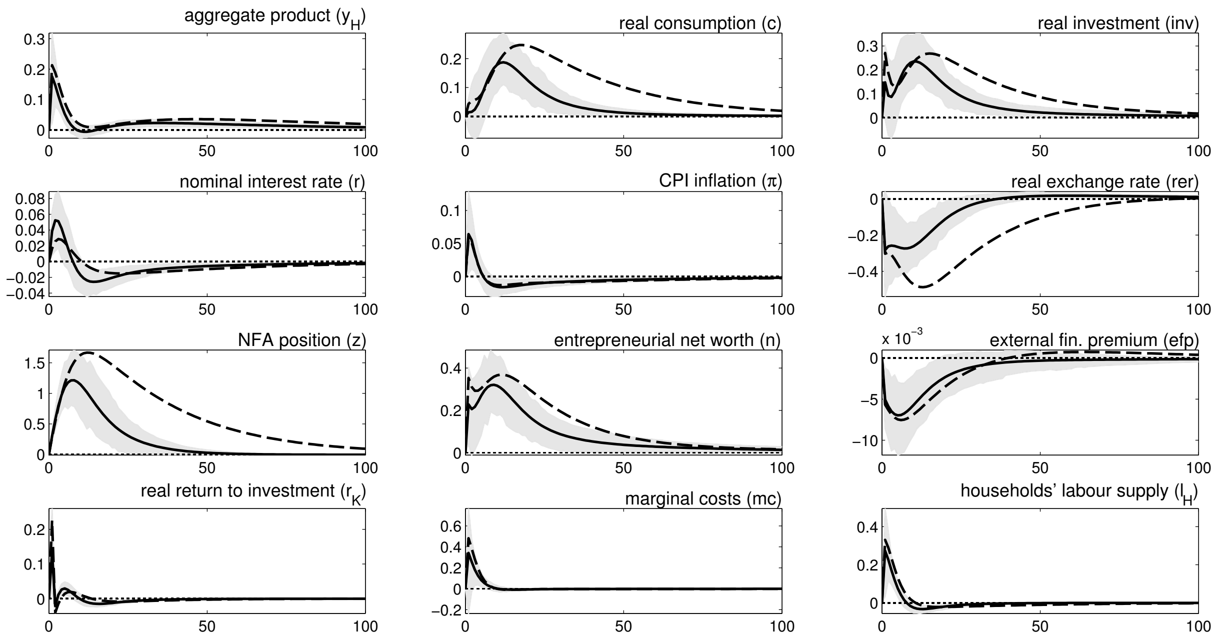
Figure C.35: Impulse responses to net worth shock, SK



Source: Author.

Note: Per cent deviations caused by 1% shock are depicted, solid line - SK, dashed line - CZ.

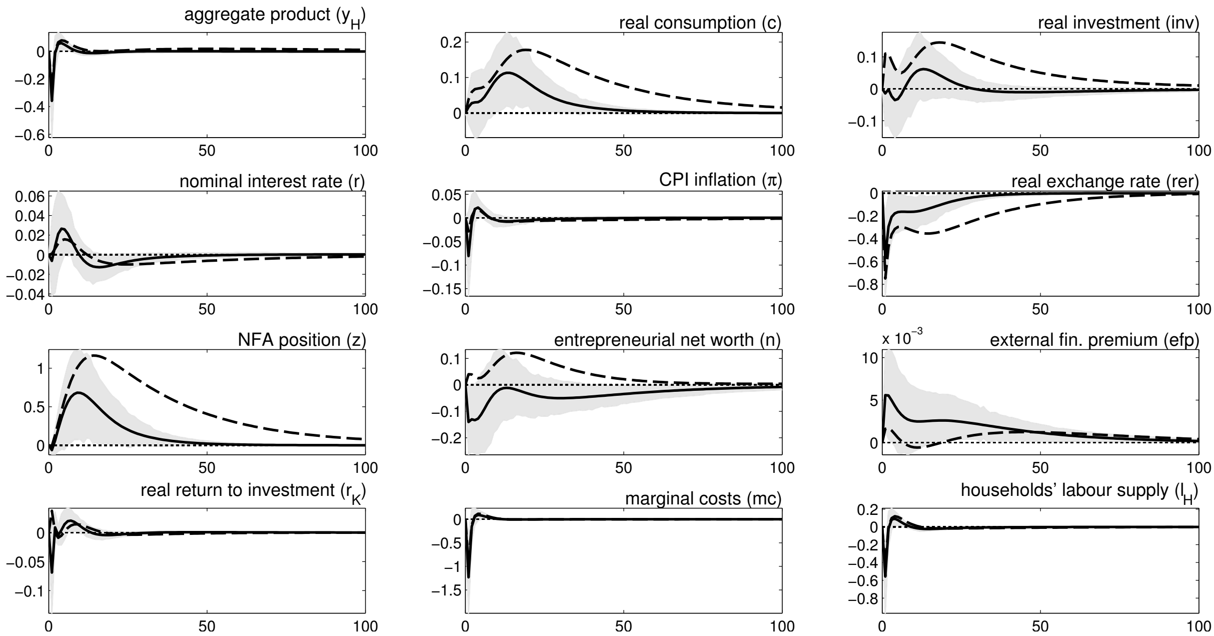
Figure C.36: Impulse responses to foreign output shock, SK



Source: Author.

Note: Per cent deviations caused by 1% shock are depicted, solid line - SK, dashed line - CZ.

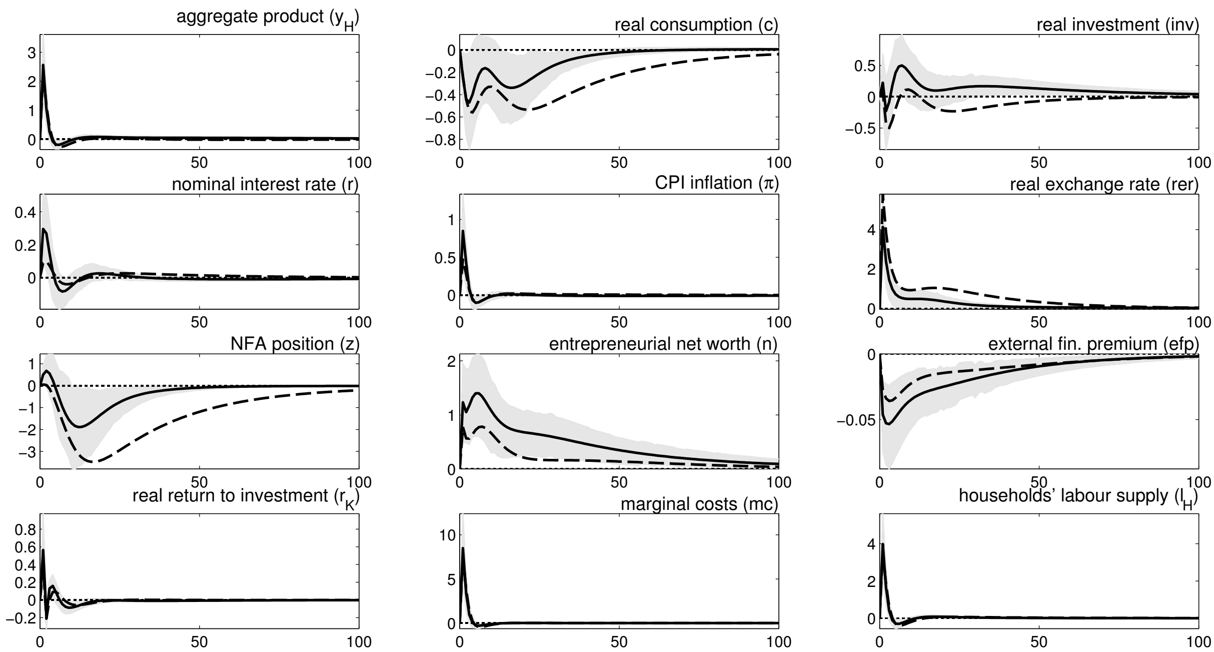
Figure C.37: Impulse responses to foreign inflation shock, SK



Source: Author.

Note: Per cent deviations caused by 1% shock are depicted, solid line - SK, dashed line - CZ.

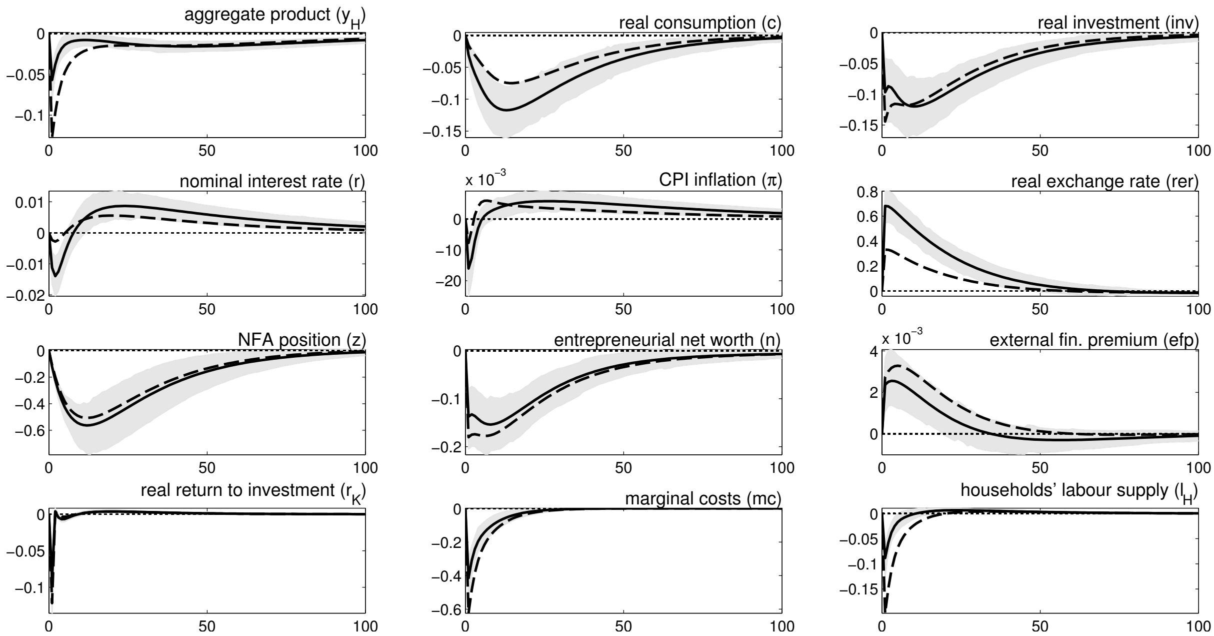
Figure C.38: Impulse responses to foreign interest rate shock, SK



Source: Author.

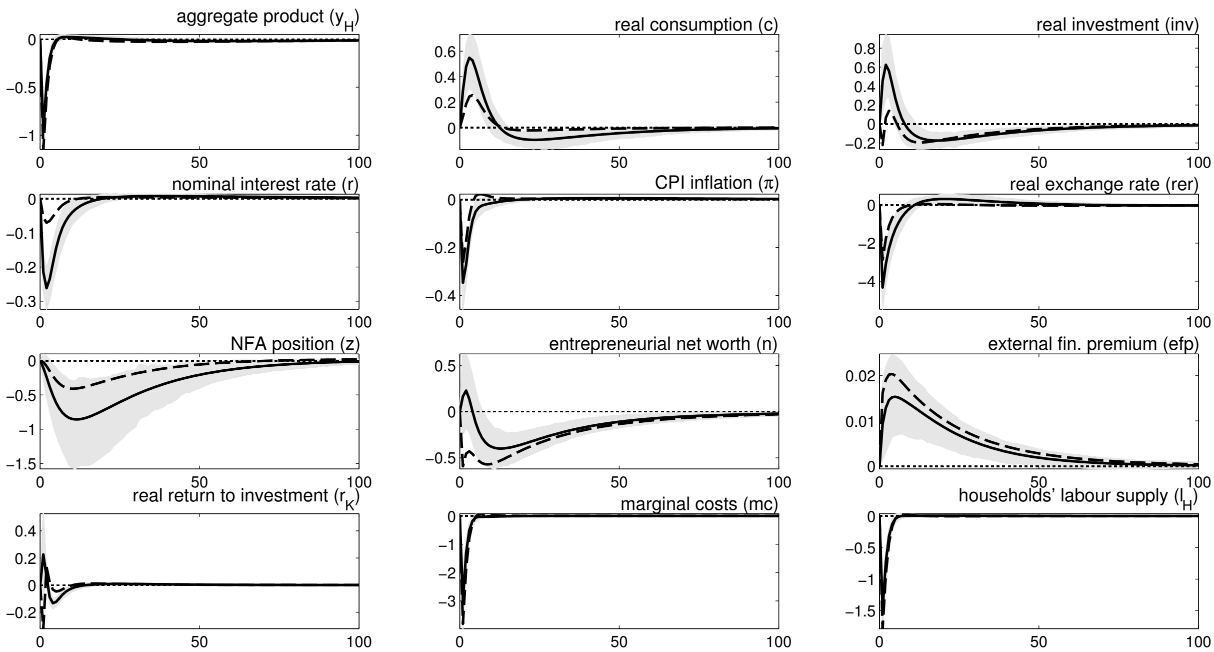
Note: Per cent deviations caused by 1% shock are depicted, solid line - SK, dashed line - CZ.

Figure C.39: Impulse responses to law of one price gap shock, PL



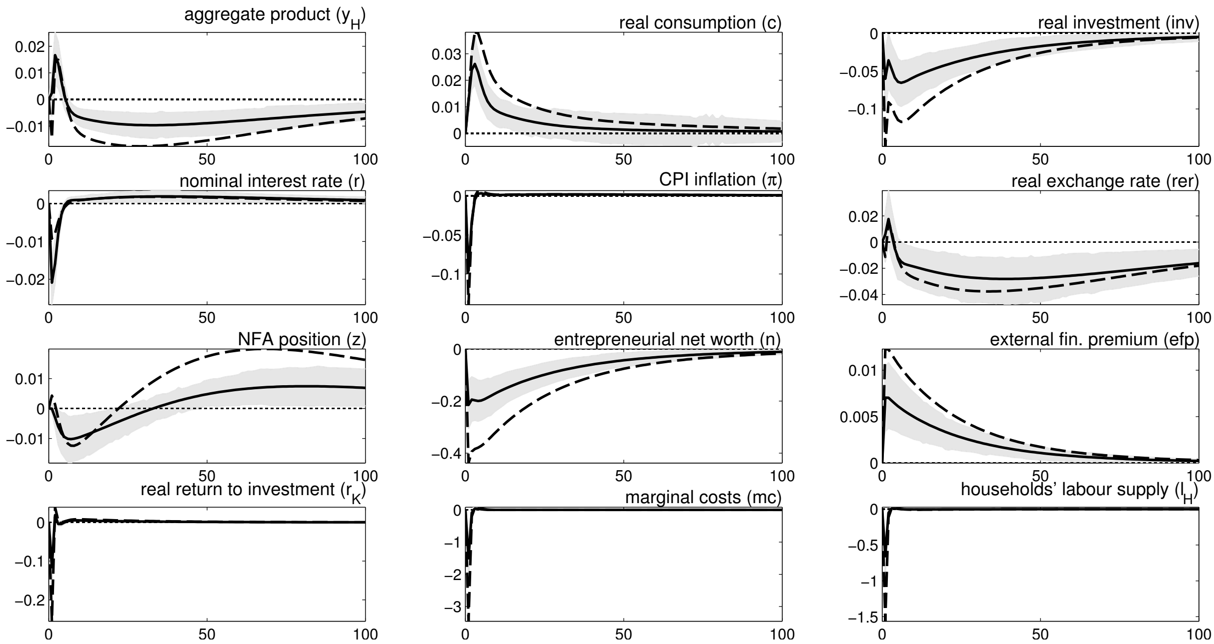
Source: Author.
Note: Per cent deviations caused by 1% shock are depicted, solid line - PL, dashed line - CZ.

Figure C.40: Impulse responses to debt-elastic risk premium shock, PL



Source: Author.
Note: Per cent deviations caused by 1% shock are depicted, solid line - PL, dashed line - CZ.

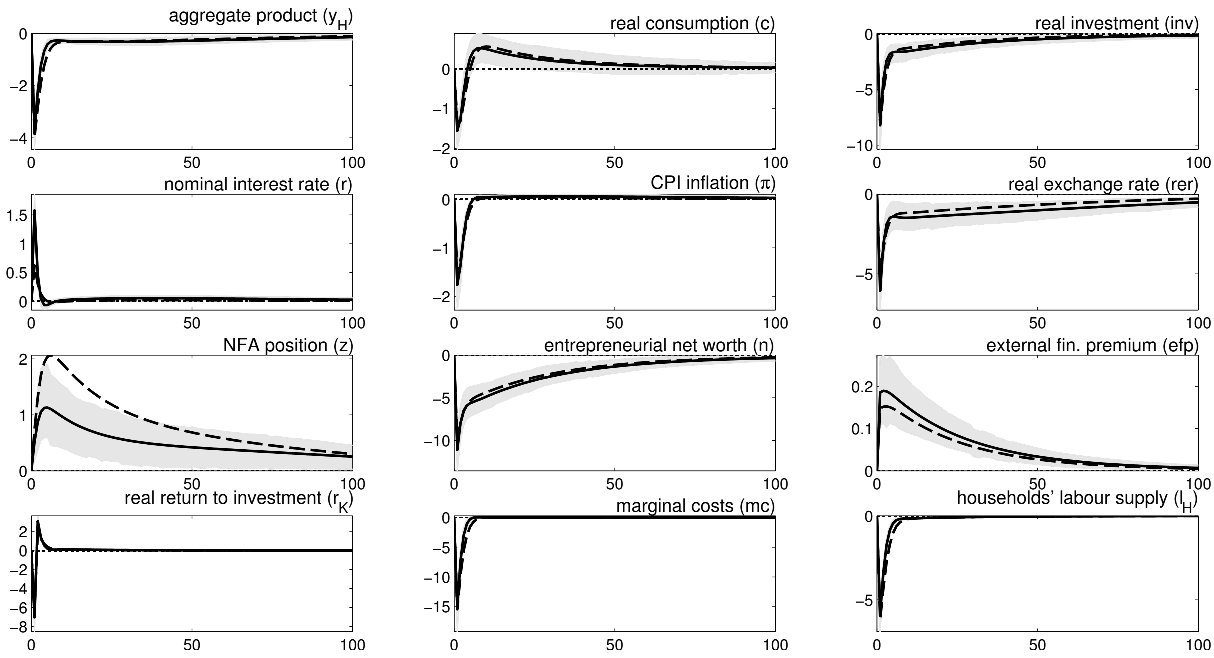
Figure C.41: Impulse responses to productivity shock, PL



Source: Author.

Note: Per cent deviations caused by 1% shock are depicted, solid line - PL, dashed line - CZ.

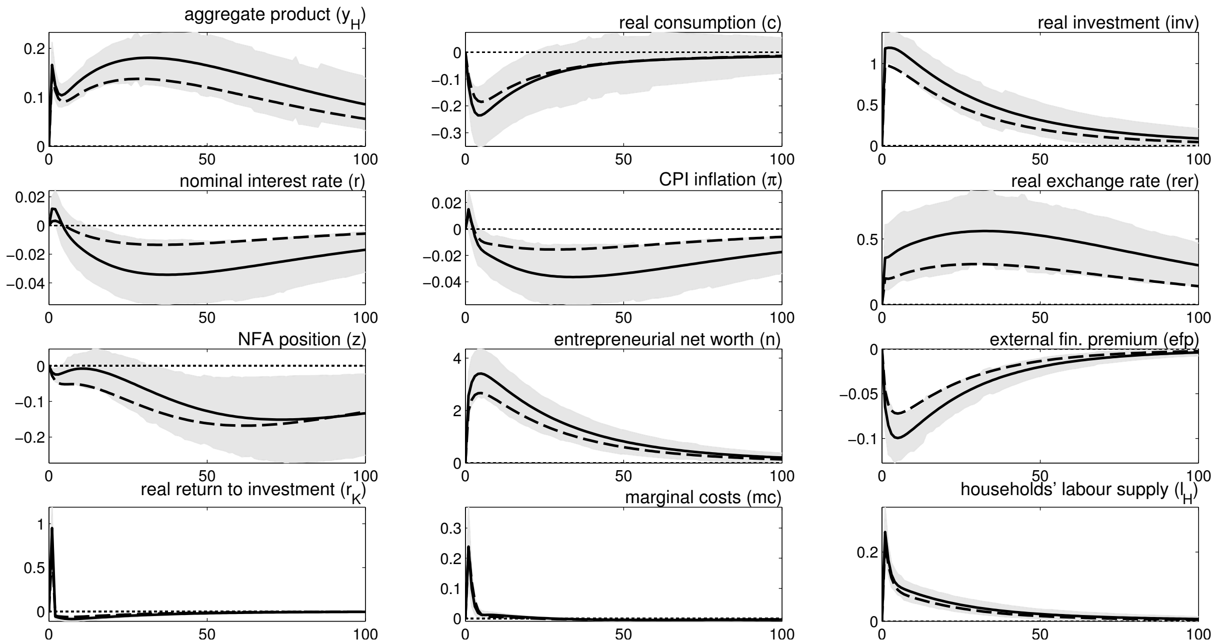
Figure C.42: Impulse responses to monetary policy shock, PL



Source: Author.

Note: Per cent deviations caused by 1% shock are depicted, solid line - PL, dashed line - CZ.

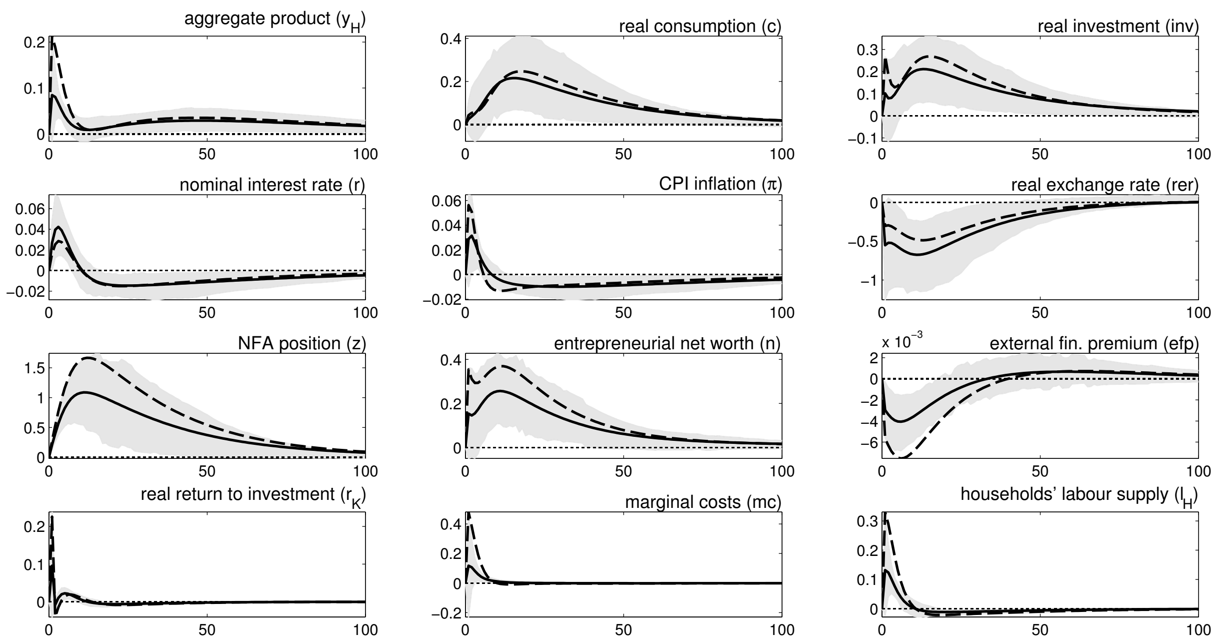
Figure C.43: Impulse responses to net worth shock, PL



Source: Author.

Note: Per cent deviations caused by 1% shock are depicted, solid line - PL, dashed line - CZ.

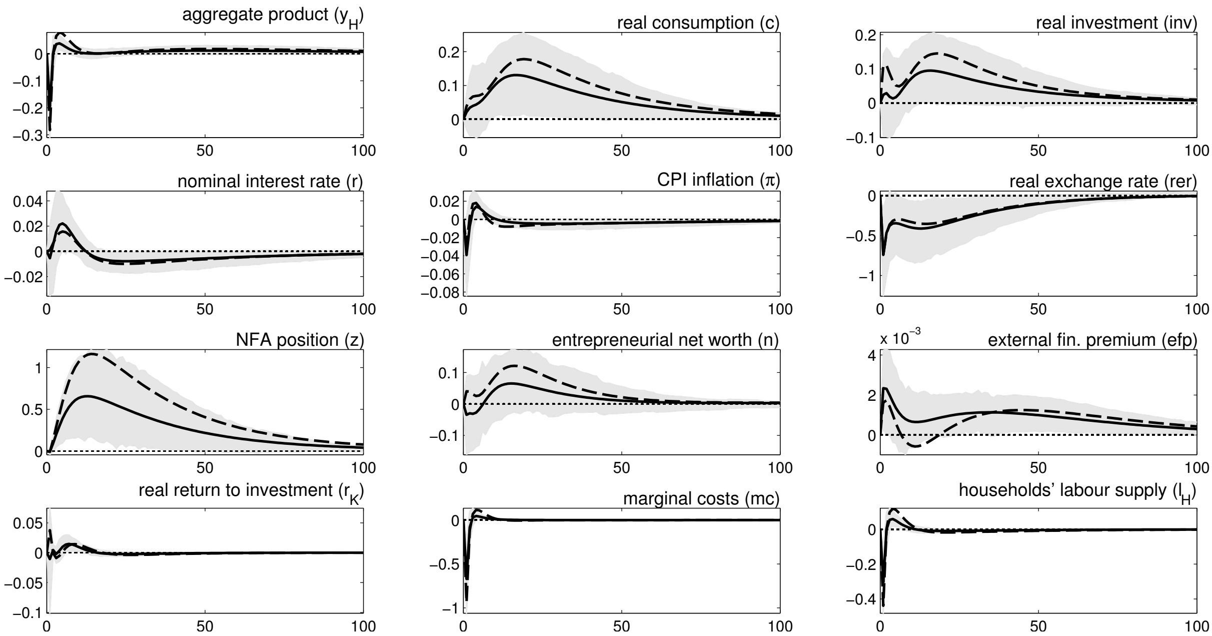
Figure C.44: Impulse responses to foreign output shock, PL



Source: Author.

Note: Per cent deviations caused by 1% shock are depicted, solid line - PL, dashed line - CZ.

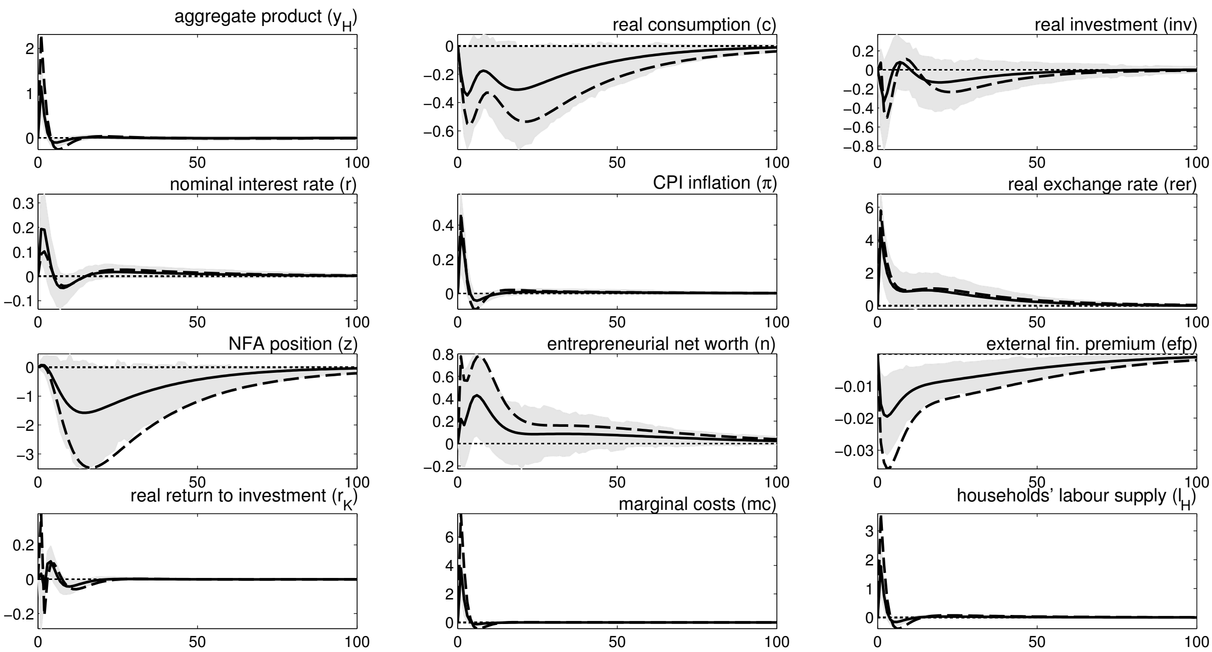
Figure C.45: Impulse responses to foreign inflation shock, PL



Source: Author.

Note: Per cent deviations caused by 1% shock are depicted, solid line - PL, dashed line - CZ.

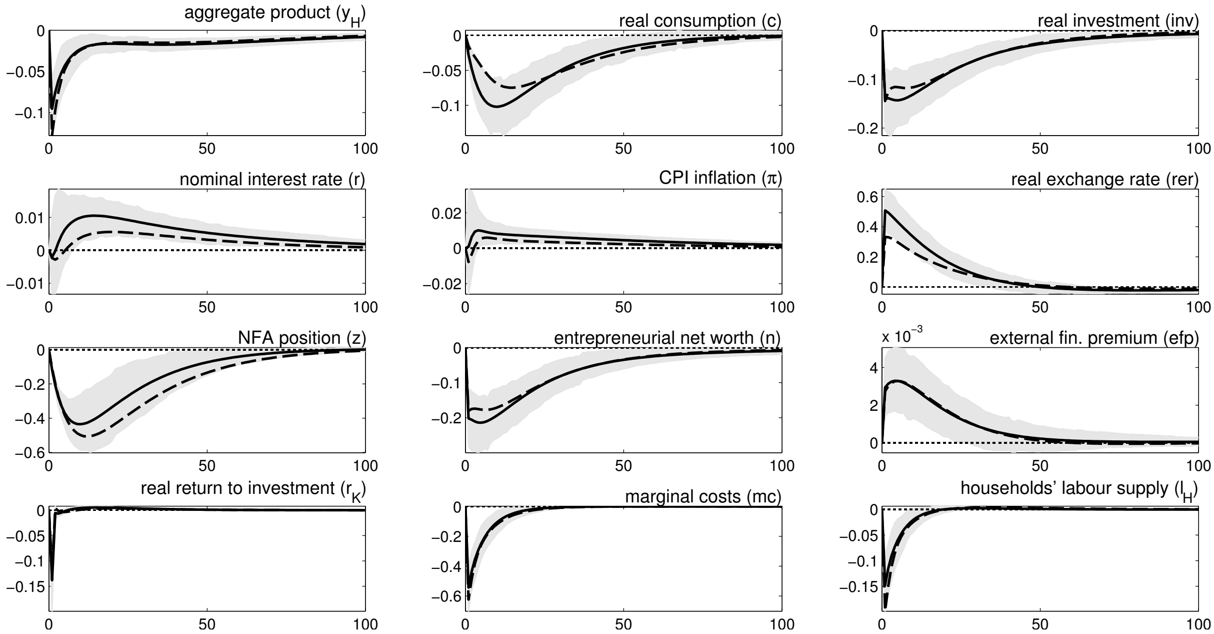
Figure C.46: Impulse responses to foreign interest rate shock, PL



Source: Author.

Note: Per cent deviations caused by 1% shock are depicted, solid line - PL, dashed line - CZ.

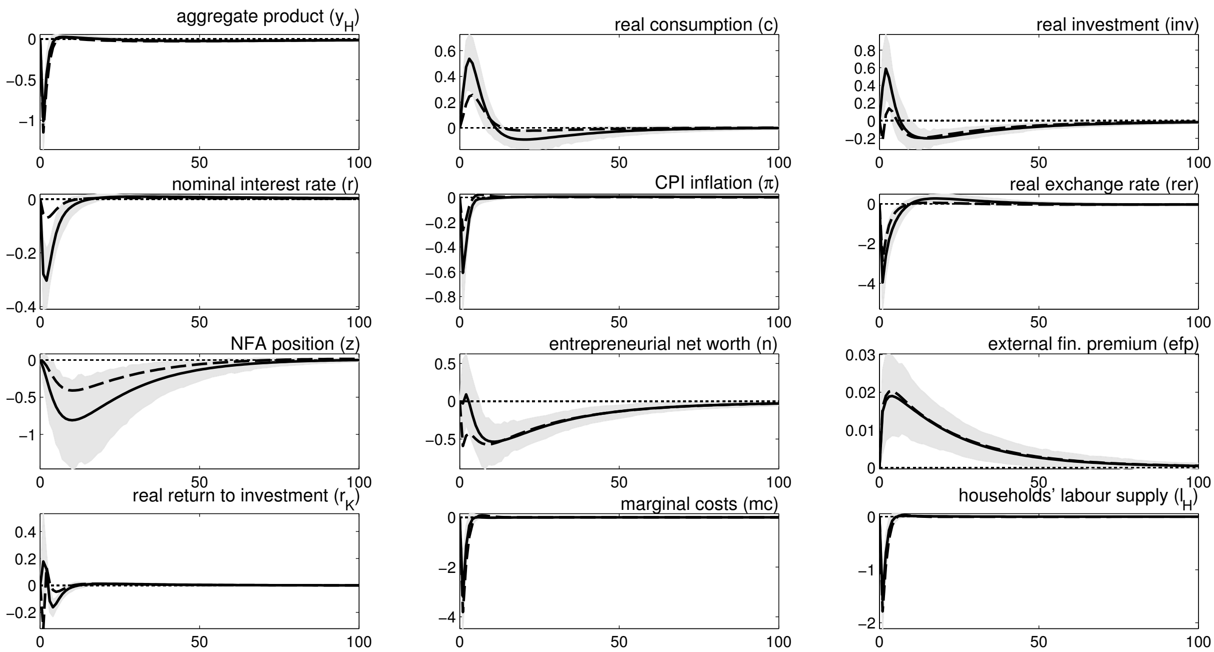
Figure C.47: Impulse responses to law of one price gap shock, HU



Source: Author.

Note: Per cent deviations caused by 1% shock are depicted, solid line - HU, dashed line - CZ.

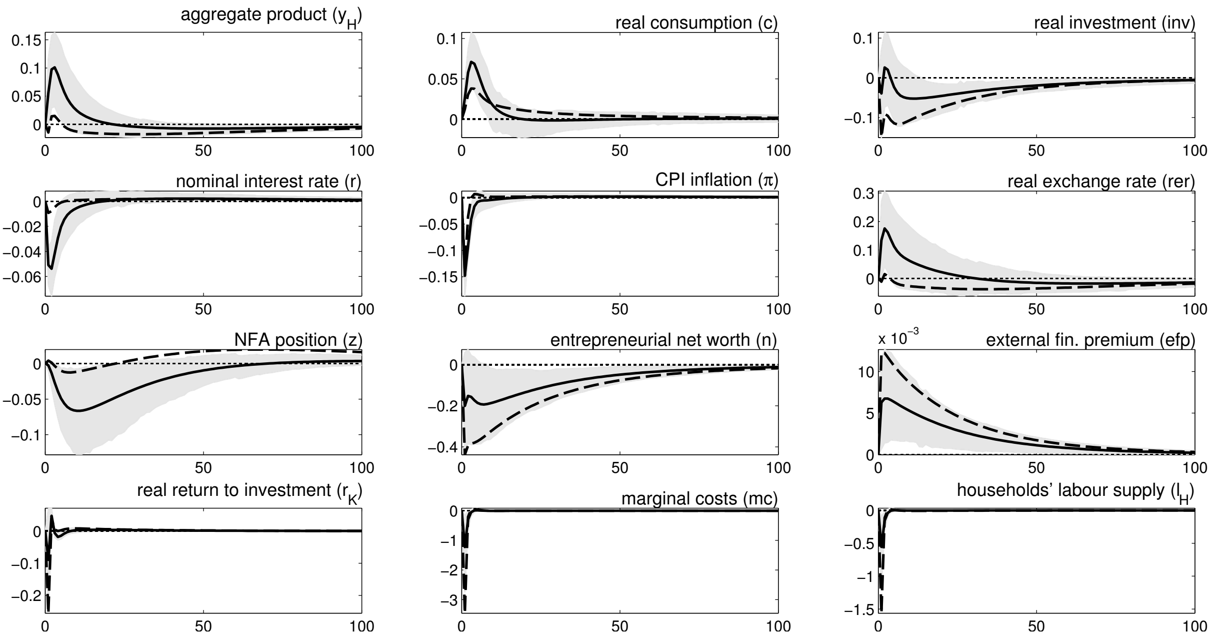
Figure C.48: Impulse responses to debt-elastic risk premium shock, HU



Source: Author.

Note: Per cent deviations caused by 1% shock are depicted, solid line - HU, dashed line - CZ.

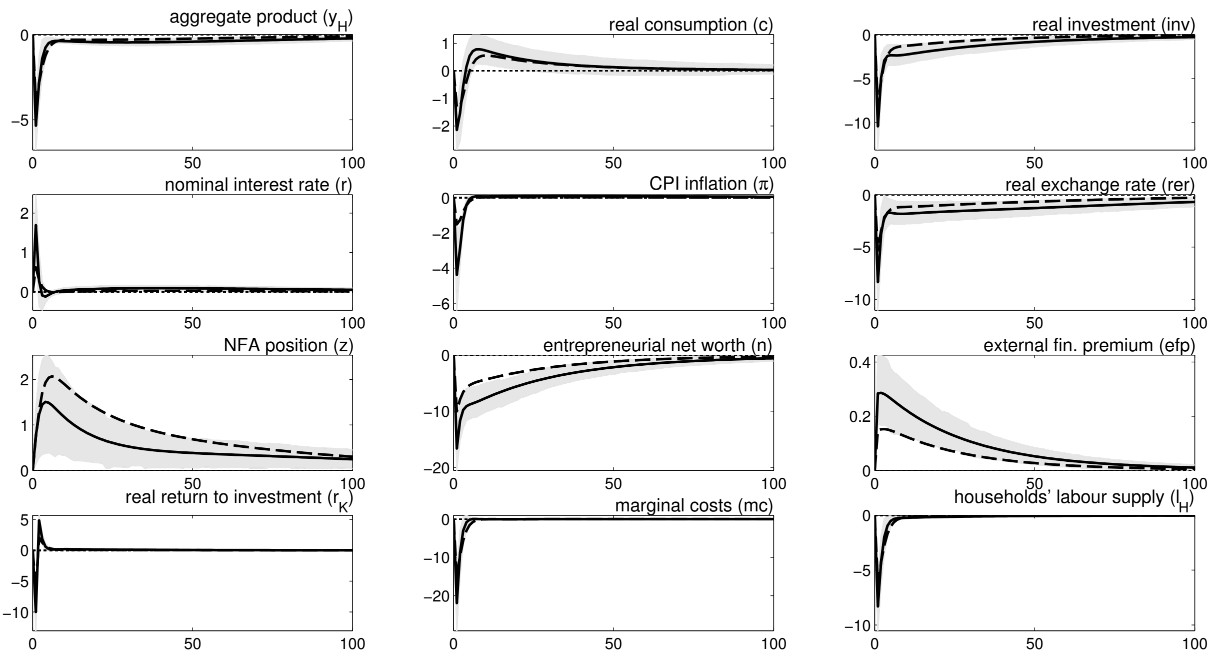
Figure C.49: Impulse responses to productivity shock, HU



Source: Author.

Note: Per cent deviations caused by 1% shock are depicted, solid line - HU, dashed line - CZ.

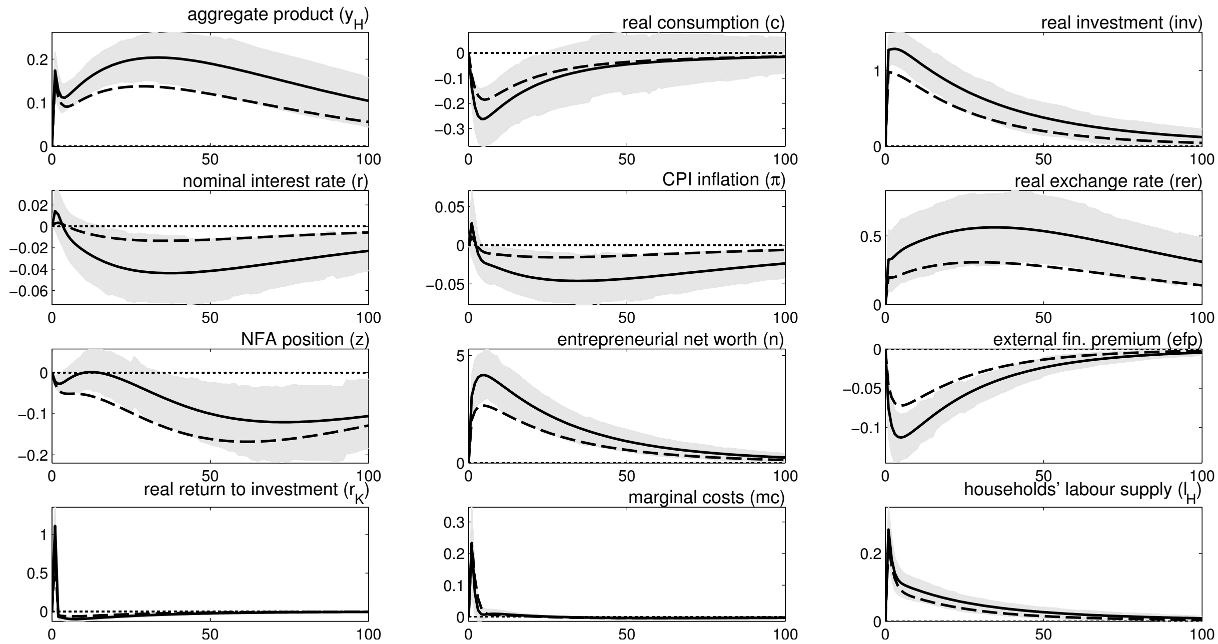
Figure C.50: Impulse responses to monetary policy shock, HU



Source: Author.

Note: Per cent deviations caused by 1% shock are depicted, solid line - HU, dashed line - CZ.

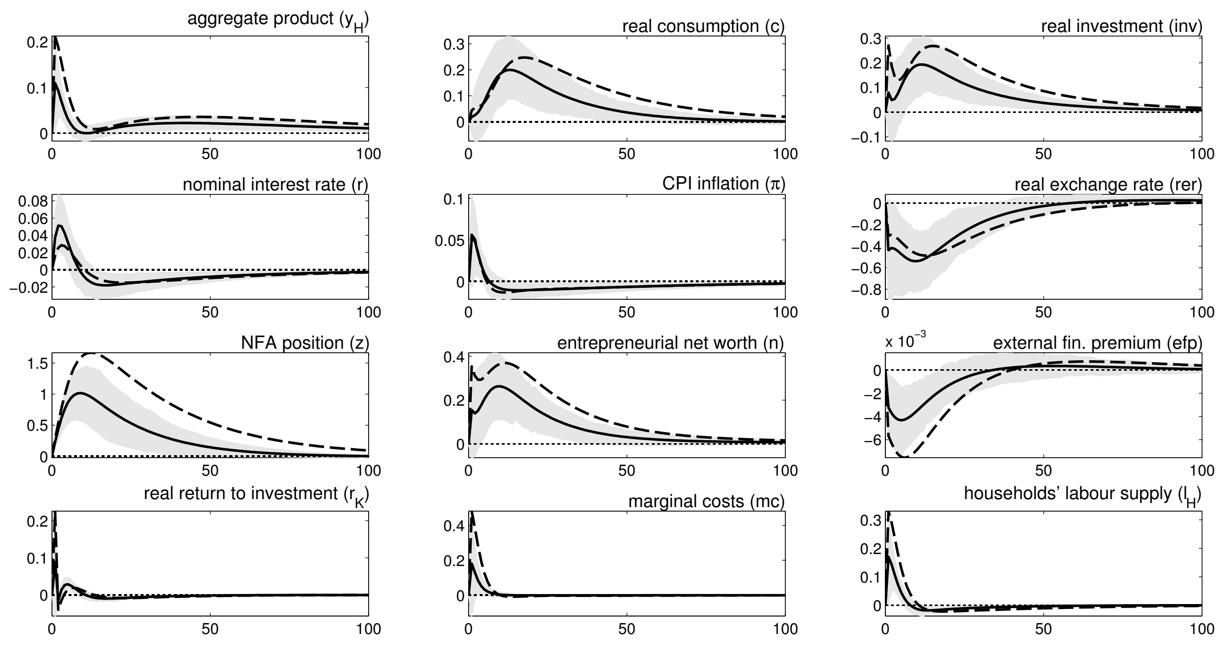
Figure C.51: Impulse responses to net worth shock, HU



Source: Author.

Note: Per cent deviations caused by 1% shock are depicted, solid line - HU, dashed line - CZ.

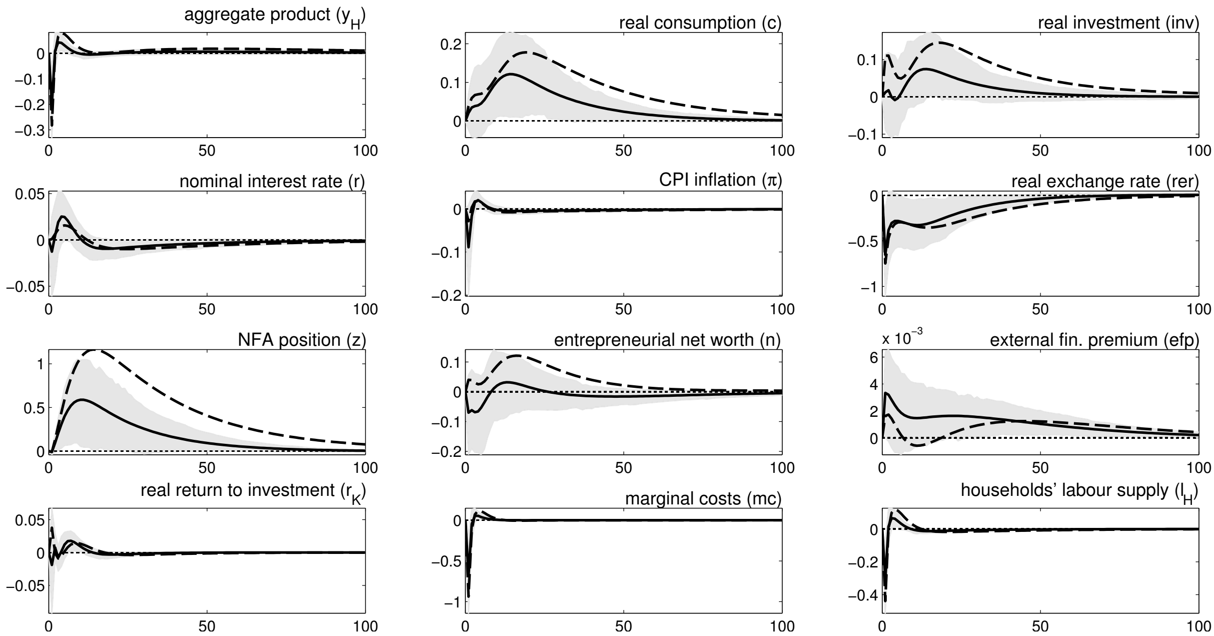
Figure C.52: Impulse responses to foreign output shock, HU



Source: Author.

Note: Per cent deviations caused by 1% shock are depicted, solid line - HU, dashed line - CZ.

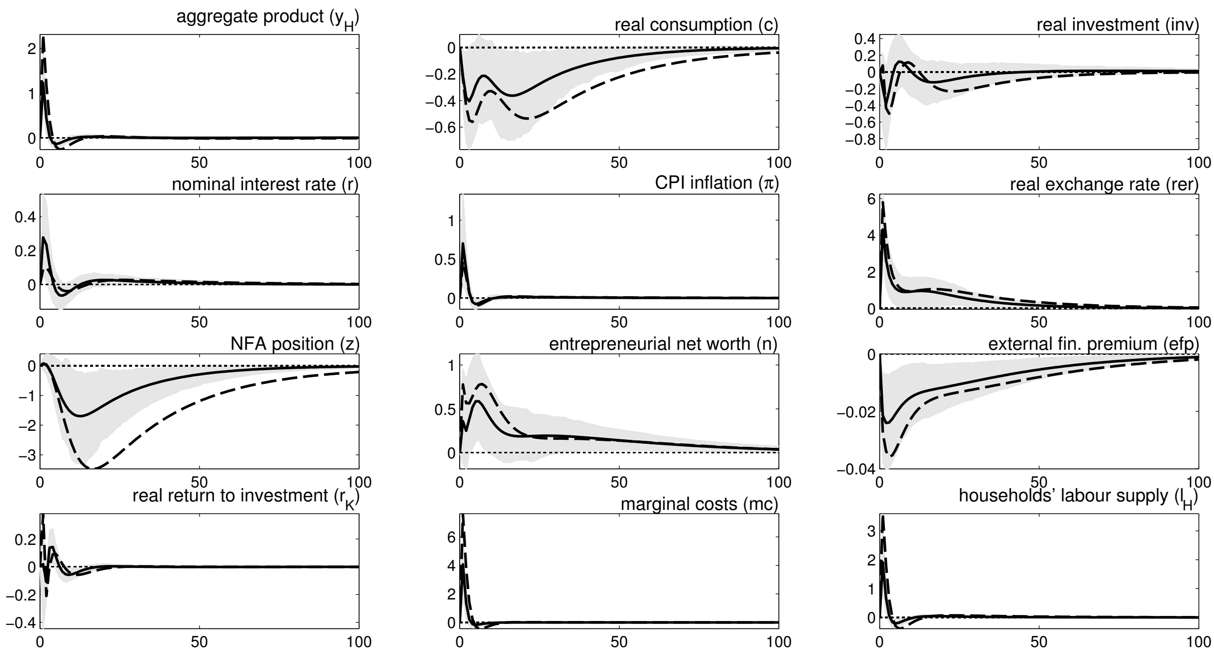
Figure C.53: Impulse responses to foreign inflation shock, HU



Source: Author.

Note: Per cent deviations caused by 1% shock are depicted, solid line - HU, dashed line - CZ.

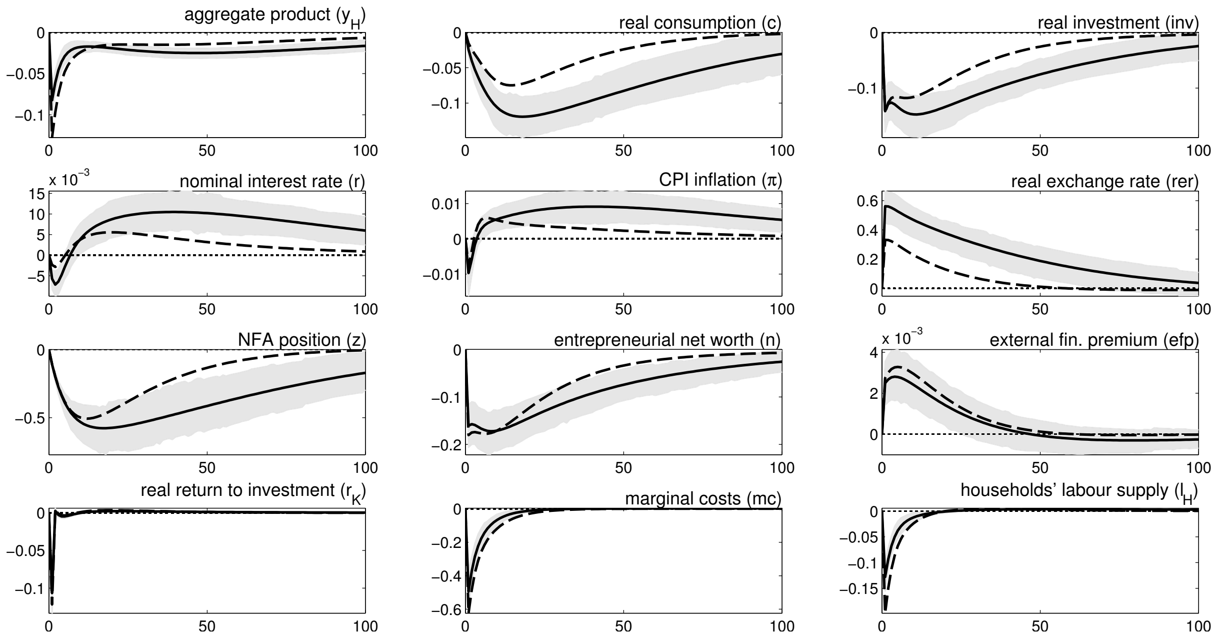
Figure C.54: Impulse responses to foreign interest rate shock, HU



Source: Author.

Note: Per cent deviations caused by 1% shock are depicted, solid line - HU, dashed line - CZ.

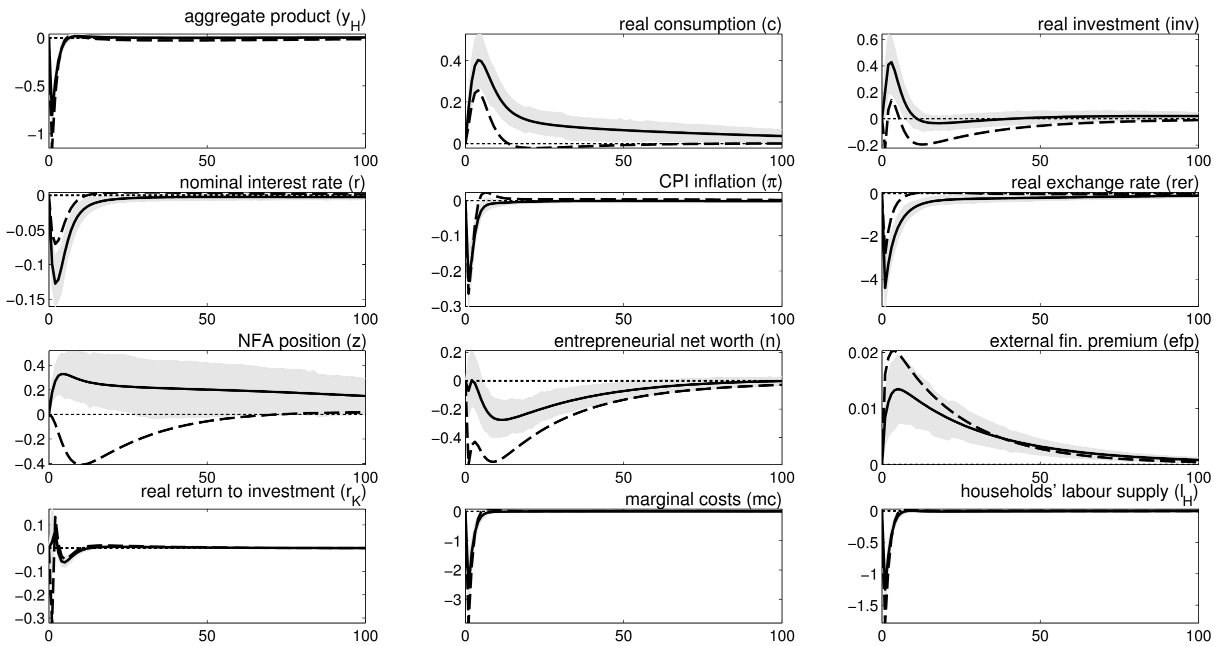
Figure C.55: Impulse responses to law of one price gap shock, EA



Source: Author.

Note: Per cent deviations caused by 1% shock are depicted, solid line - EA, dashed line - CZ.

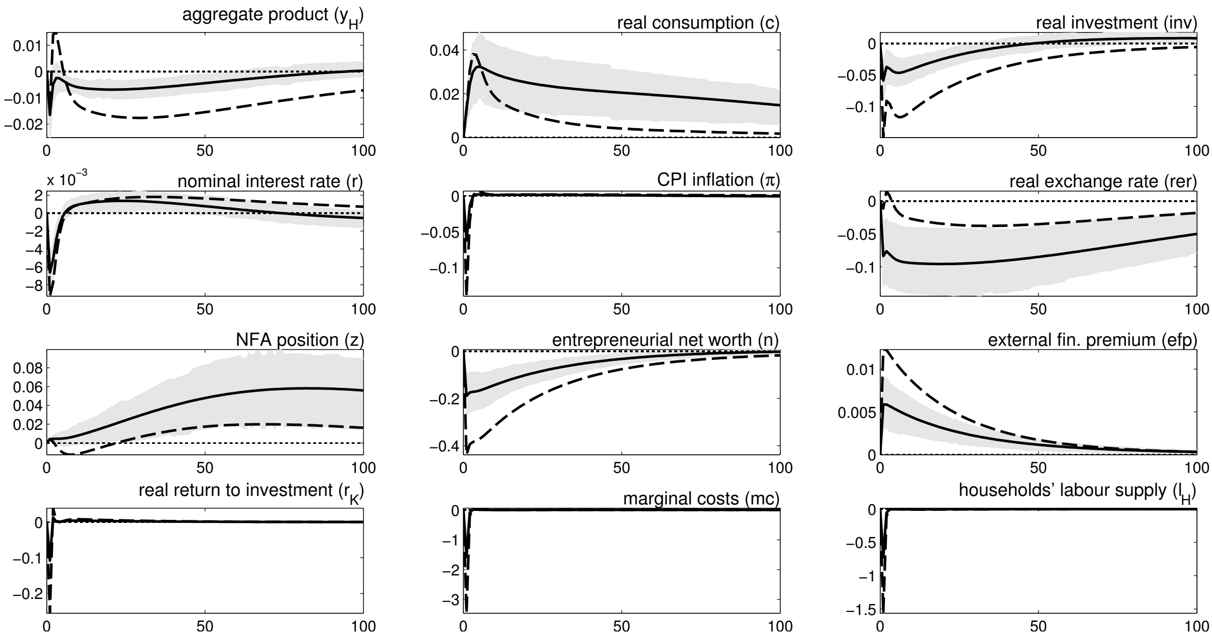
Figure C.56: Impulse responses to debt-elastic risk premium shock, EA



Source: Author.

Note: Per cent deviations caused by 1% shock are depicted, solid line - EA, dashed line - CZ.

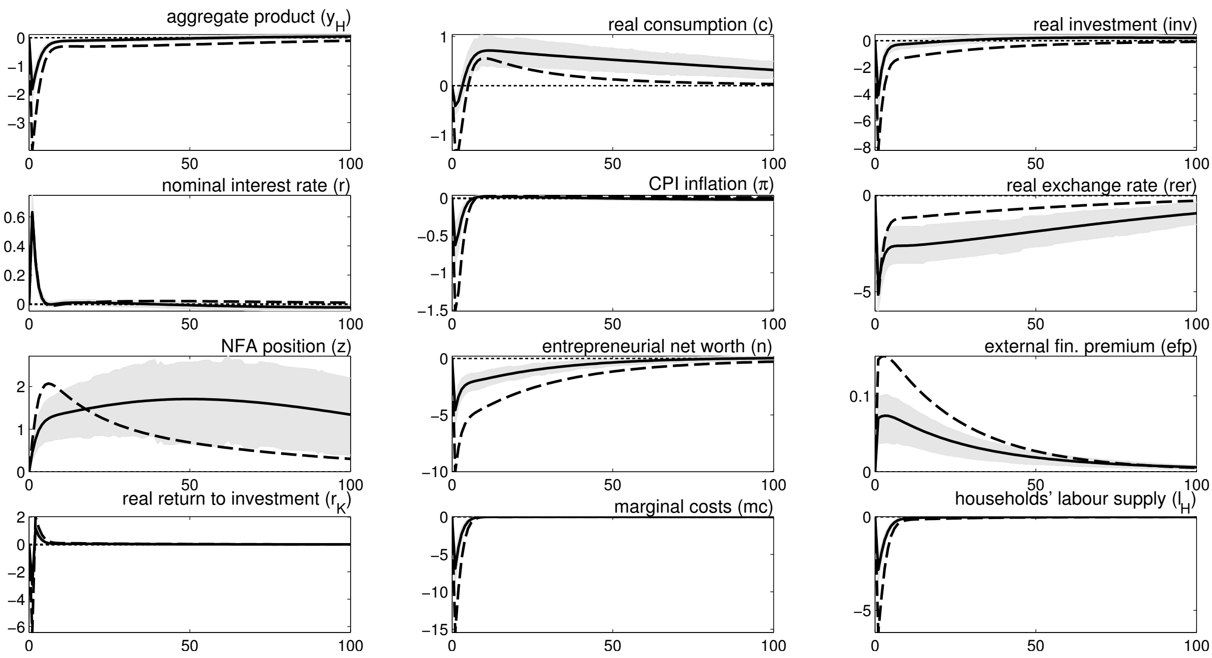
Figure C.57: Impulse responses to productivity shock, EA



Source: Author.

Note: Per cent deviations caused by 1% shock are depicted, solid line - EA, dashed line - CZ.

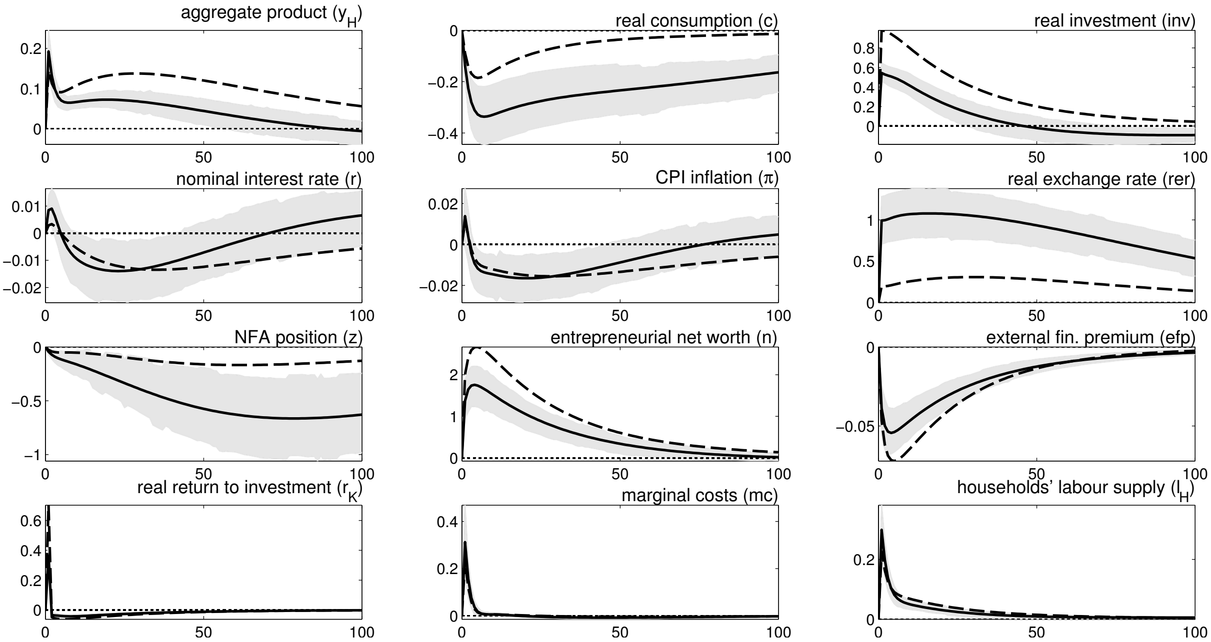
Figure C.58: Impulse responses to monetary policy shock, EA



Source: Author.

Note: Per cent deviations caused by 1% shock are depicted, solid line - EA, dashed line - CZ.

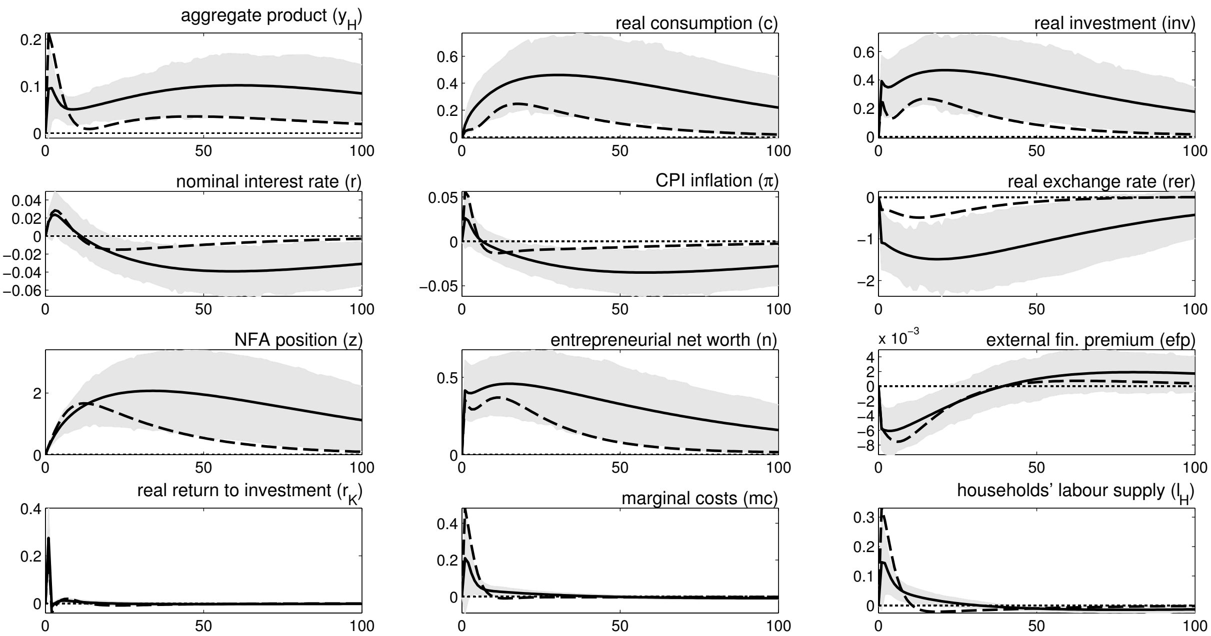
Figure C.59: Impulse responses to net worth shock, EA



Source: Author.

Note: Per cent deviations caused by 1% shock are depicted, solid line - EA, dashed line - CZ.

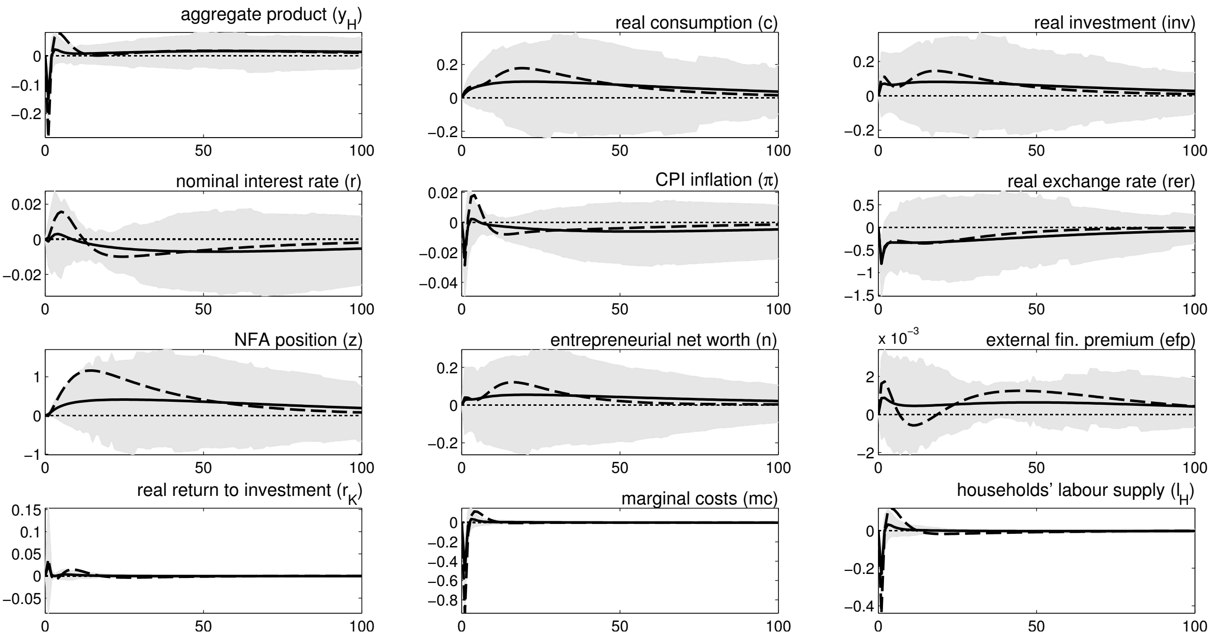
Figure C.60: Impulse responses to foreign output shock, EA



Source: Author.

Note: Per cent deviations caused by 1% shock are depicted, solid line - EA, dashed line - CZ.

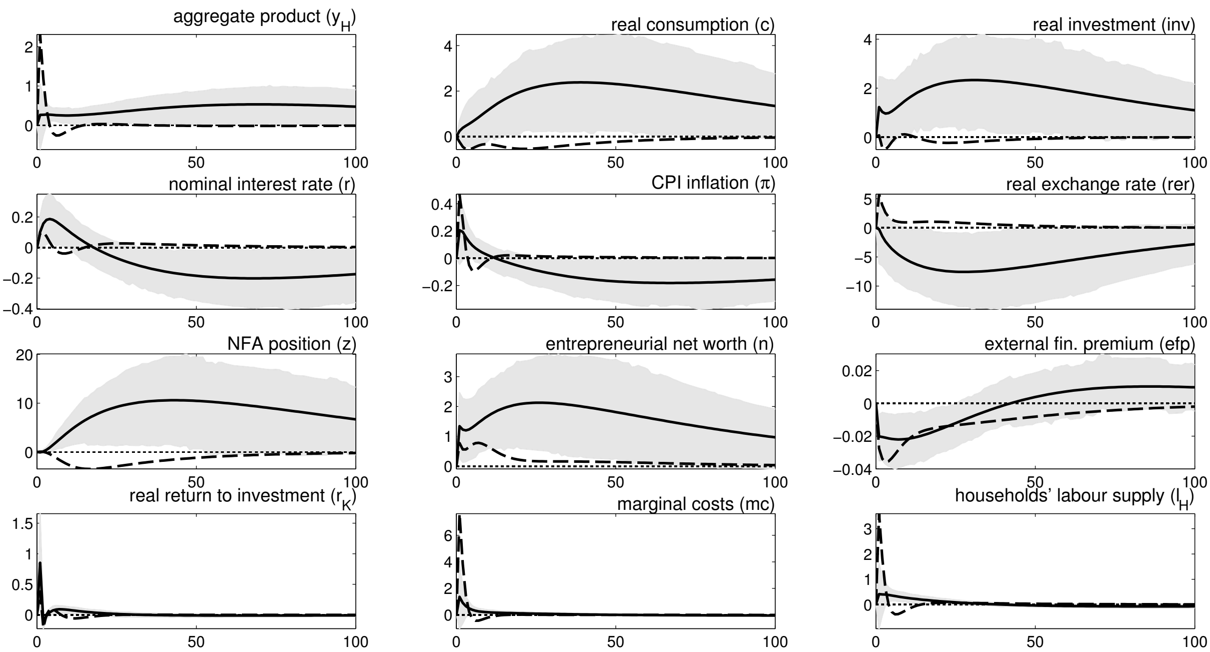
Figure C.61: Impulse responses to foreign inflation shock, EA



Source: Author.

Note: Per cent deviations caused by 1% shock are depicted, solid line - EA, dashed line - CZ.

Figure C.62: Impulse responses to foreign interest rate shock, EA

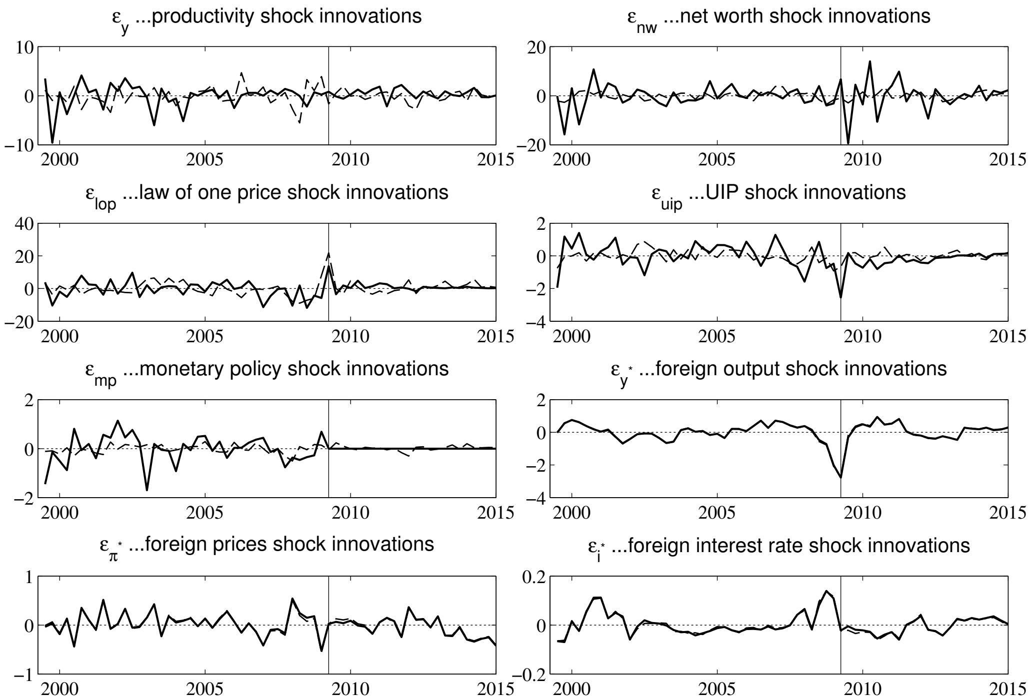


Source: Author.

Note: Per cent deviations caused by 1% shock are depicted, solid line - EA, dashed line - CZ.

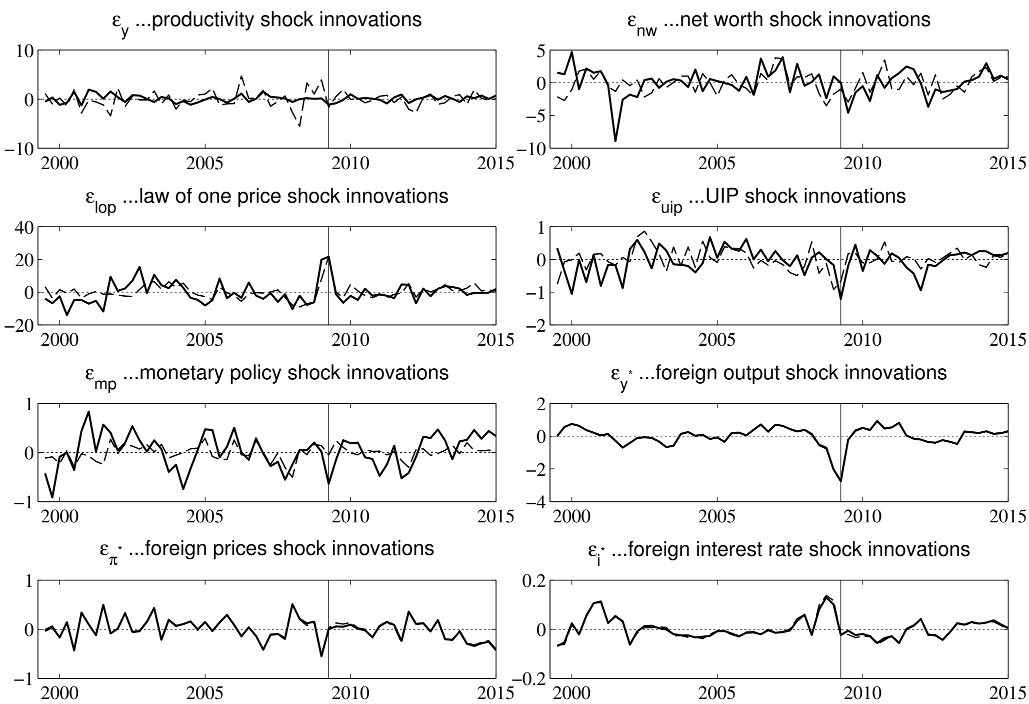
C.5 Filtered shock innovations

Figure C.63: Filtered shock innovations, SK



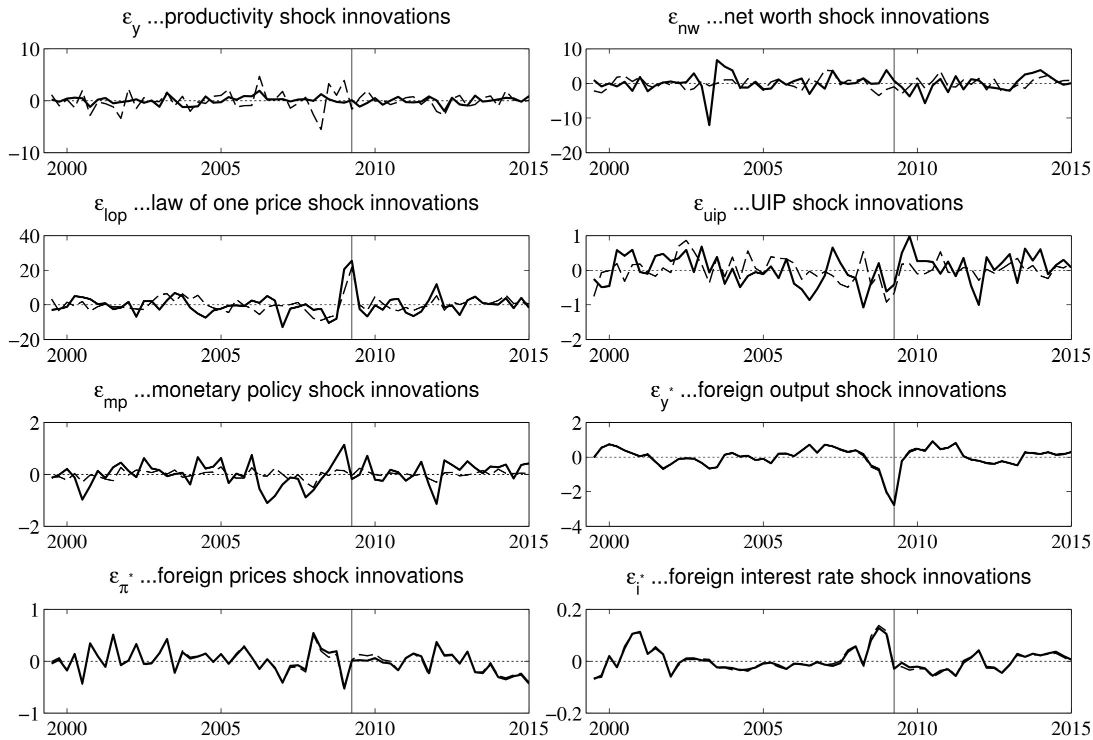
Source: Author.
Note: Shock innovations are depicted in per cent, solid line - SK, dashed line - CZ, vertical line - 2009Q1.

Figure C.64: Filtered shock innovations, PL



Source: Author.
Note: Shock innovations are depicted in per cent, solid line - PL, dashed line - CZ, vertical line - 2009Q1.

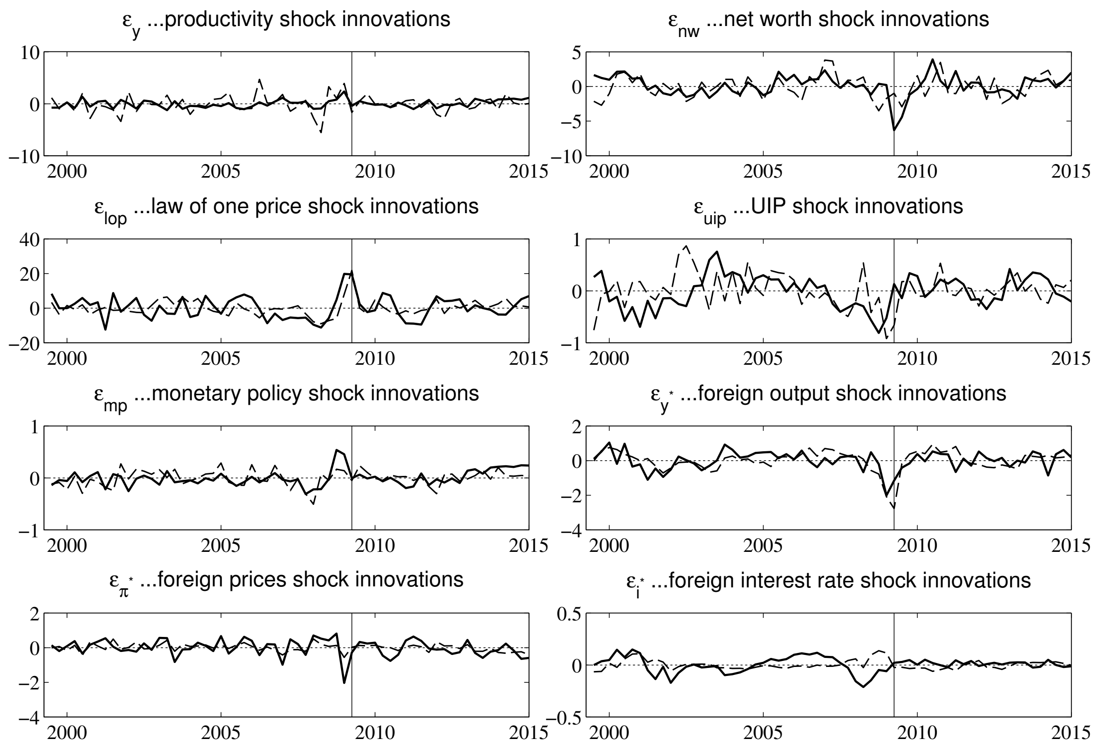
Figure C.65: Filtered shock innovations, HU



Source: Author.

Note: Shock innovations are depicted in per cent, solid line - HU, dashed line - CZ, vertical line - 2009Q1.

Figure C.66: Filtered shock innovations, EA

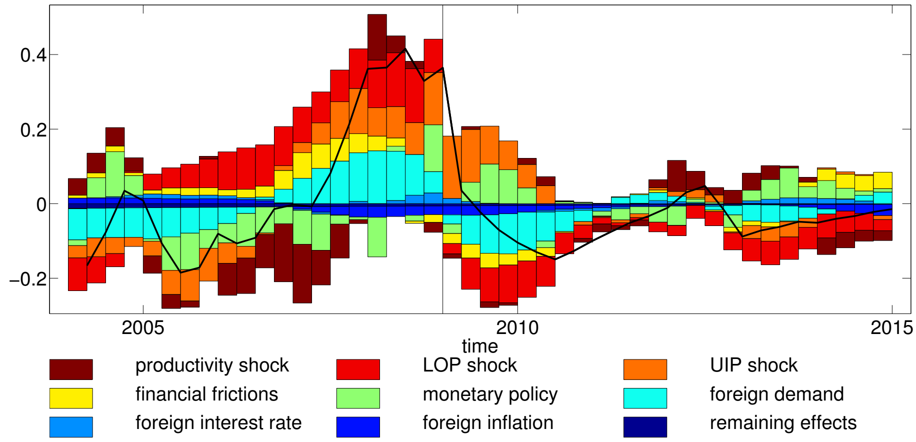


Source: Author.

Note: Shock innovations are depicted in per cent, solid line - EA, dashed line - CZ, vertical line - 2009Q1.

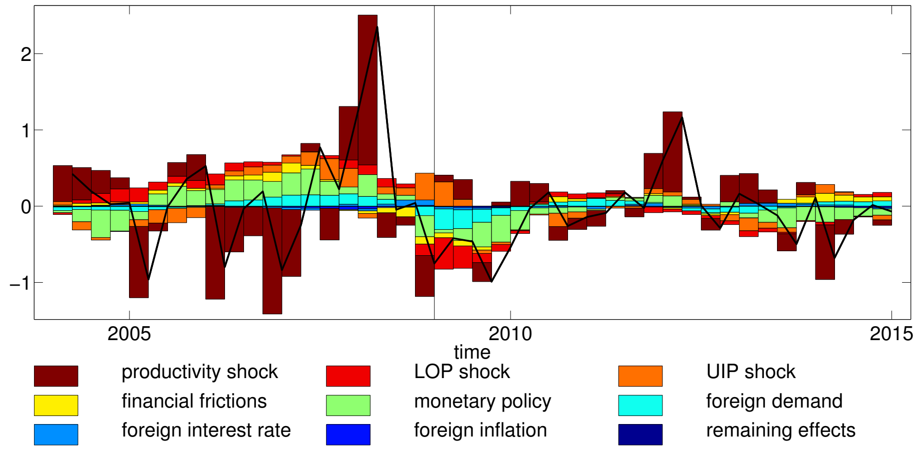
C.6 Shock decompositions

Figure C.67: Shock decomposition of nominal interest rate, CZ



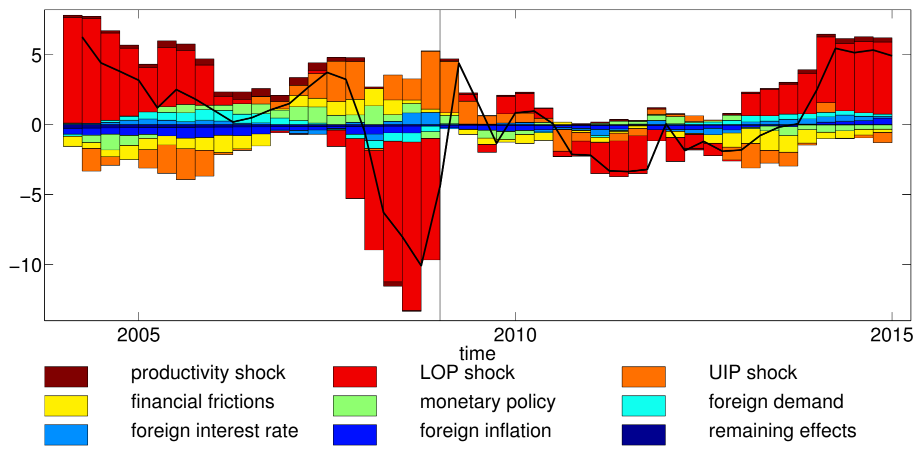
Source: Author.
Note: Per cent deviations are depicted, vertical line - 2009Q1.

Figure C.68: Shock decomposition of CPI inflation, CZ



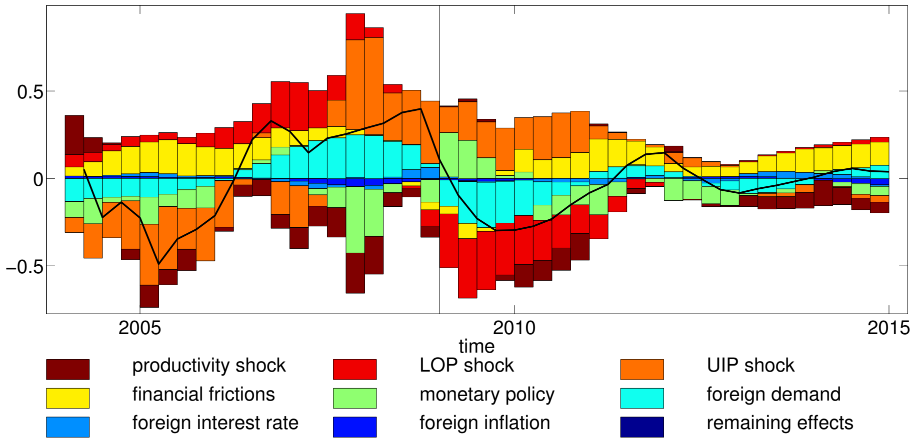
Source: Author.
Note: Per cent deviations are depicted, vertical line - 2009Q1.

Figure C.69: Shock decomposition of real exchange rate, CZ



Source: Author.
Note: Per cent deviations are depicted, vertical line - 2009Q1.

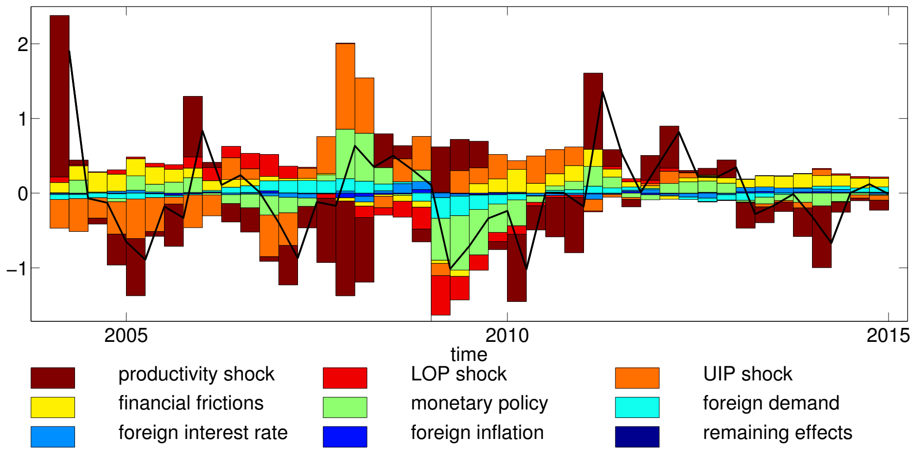
Figure C.70: Shock decomposition of nominal interest rate, SK



Source: Author.

Note: Per cent deviations are depicted, vertical line - 2009Q1.

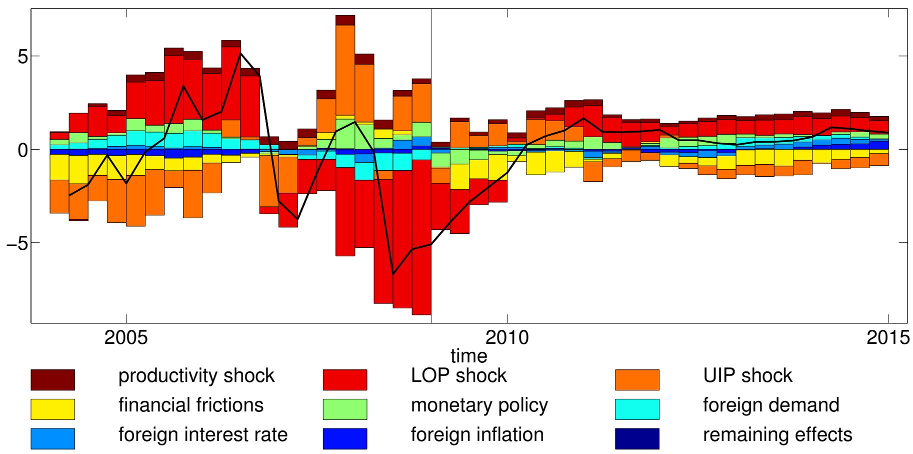
Figure C.71: Shock decomposition of CPI inflation, SK



Source: Author.

Note: Per cent deviations are depicted, vertical line - 2009Q1.

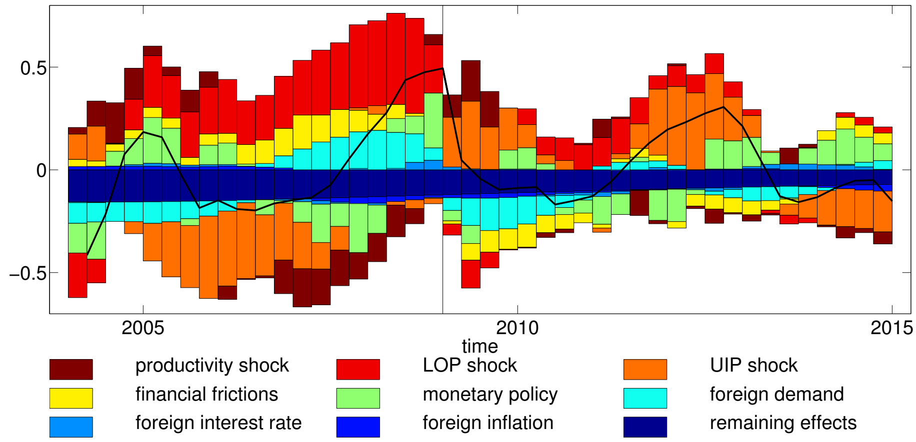
Figure C.72: Shock decomposition of real exchange rate, SK



Source: Author.

Note: Per cent deviations are depicted, vertical line - 2009Q1.

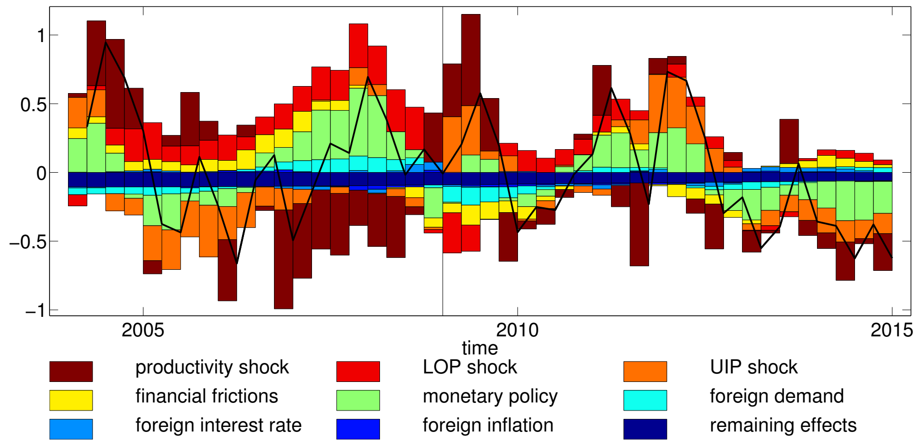
Figure C.73: Shock decomposition of nominal interest rate, PL



Source: Author.

Note: Per cent deviations are depicted, vertical line - 2009Q1.

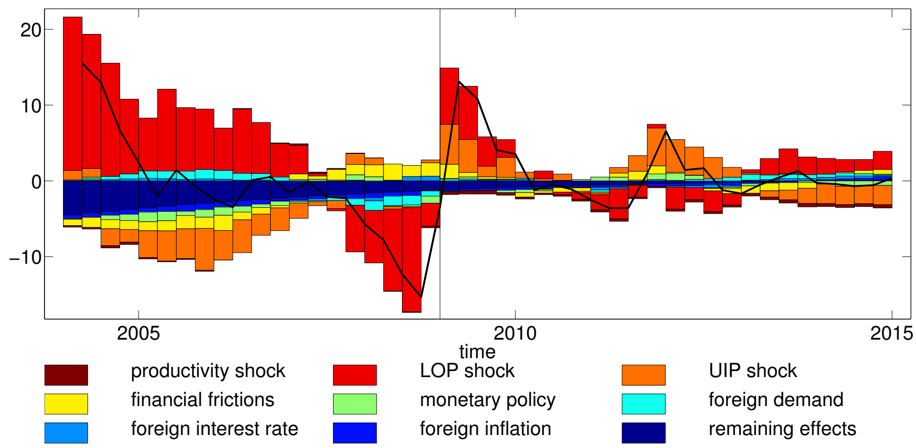
Figure C.74: Shock decomposition of CPI inflation, PL



Source: Author.

Note: Per cent deviations are depicted, vertical line - 2009Q1.

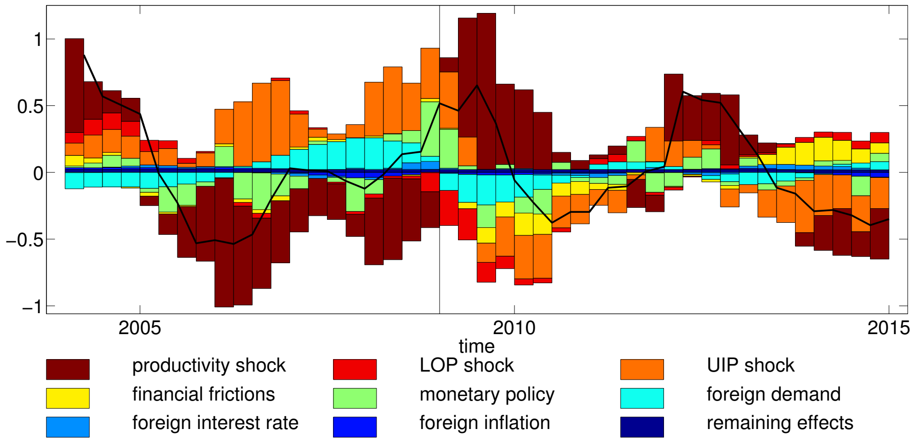
Figure C.75: Shock decomposition of real exchange rate, PL



Source: Author.

Note: Per cent deviations are depicted, vertical line - 2009Q1.

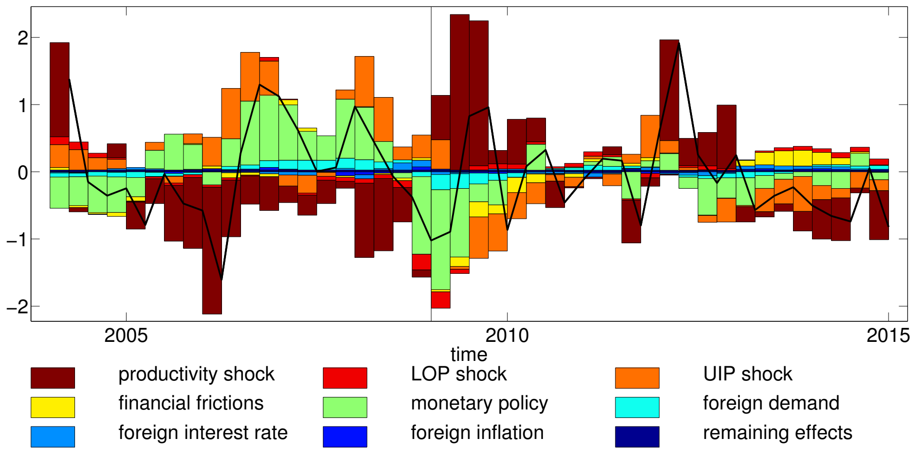
Figure C.76: Shock decomposition of nominal interest rate, HU



Source: Author.

Note: Per cent deviations are depicted, vertical line - 2009Q1.

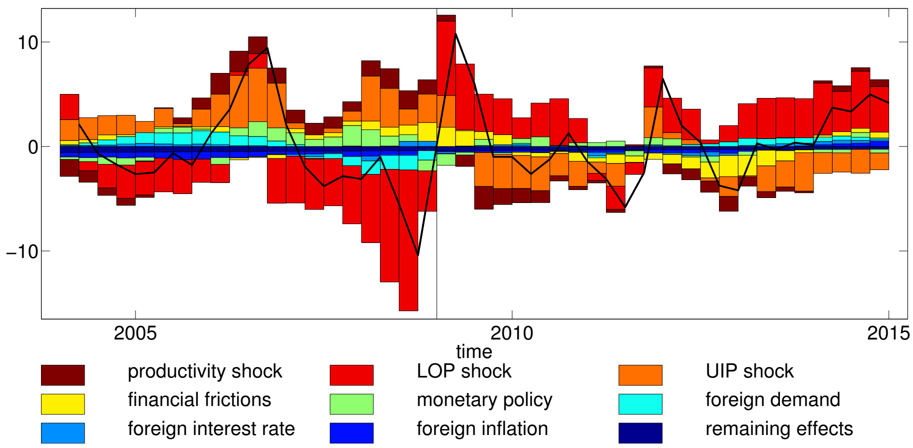
Figure C.77: Shock decomposition of CPI inflation, HU



Source: Author.

Note: Per cent deviations are depicted, vertical line - 2009Q1.

Figure C.78: Shock decomposition of real exchange rate, HU

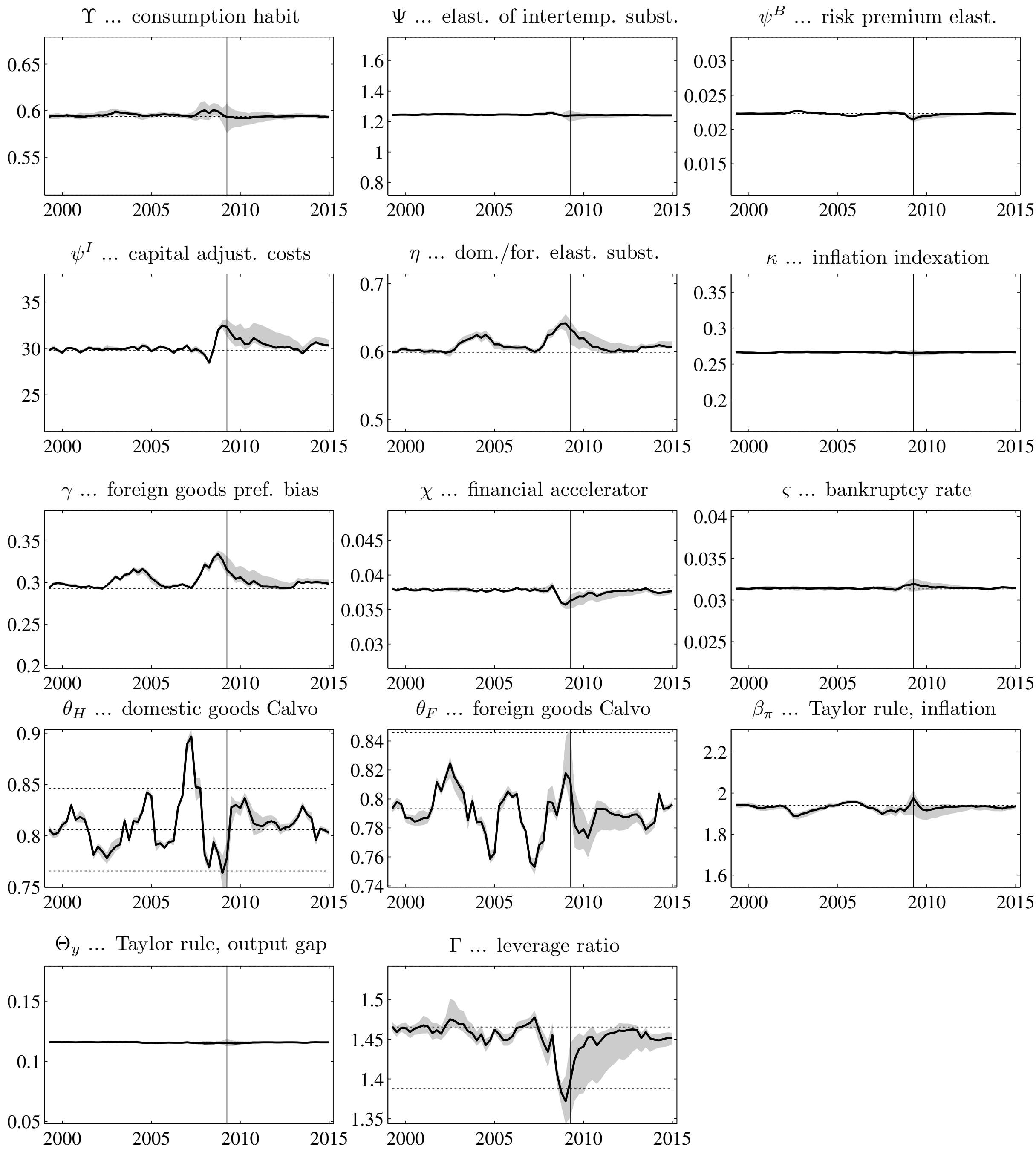


Source: Author.

Note: Per cent deviations are depicted, vertical line - 2009Q1.

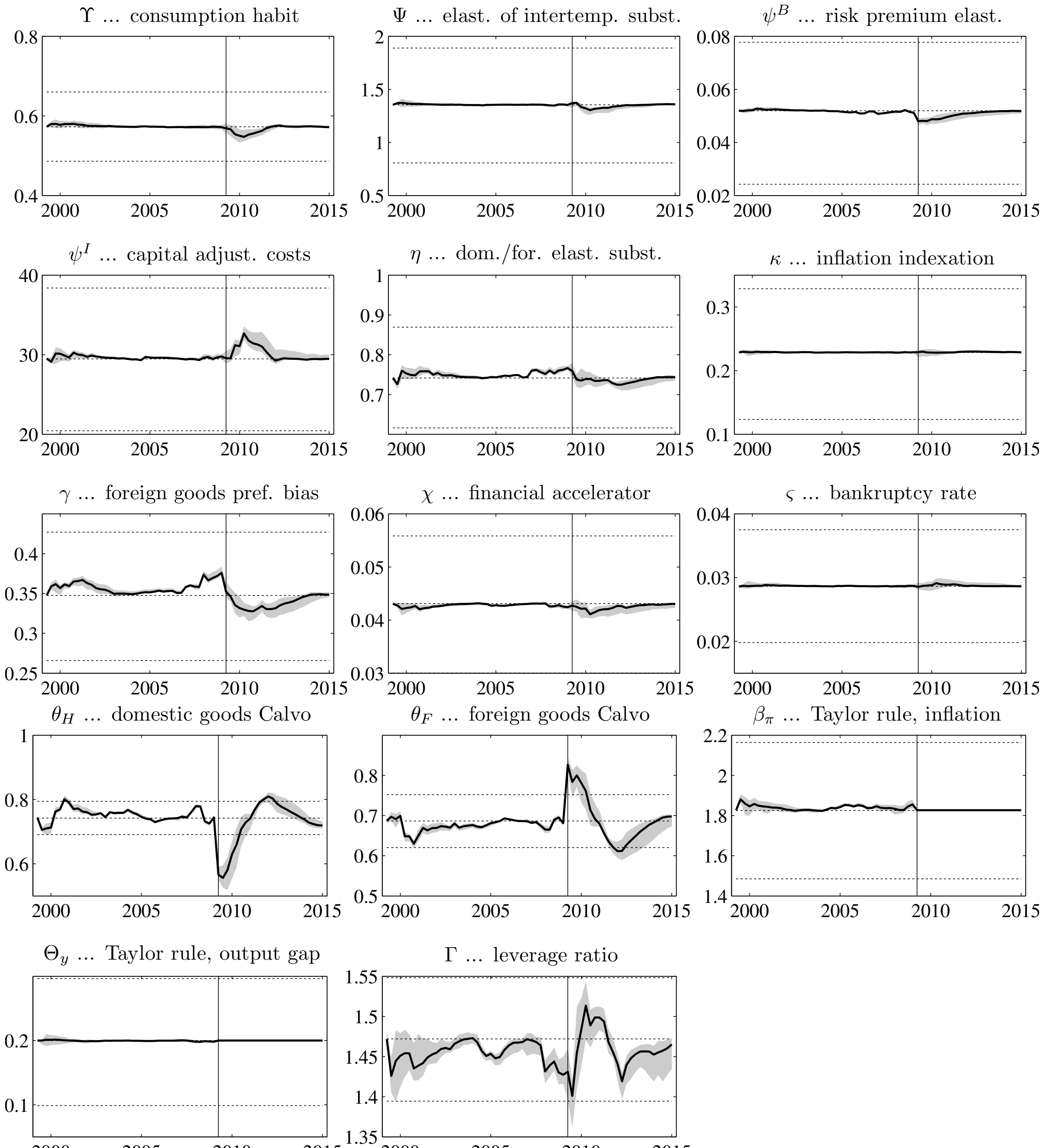
C.7 Filtered time-varying parameters

Figure C.79: Filtered time-varying parameters (95% HPDI bounds), CZ



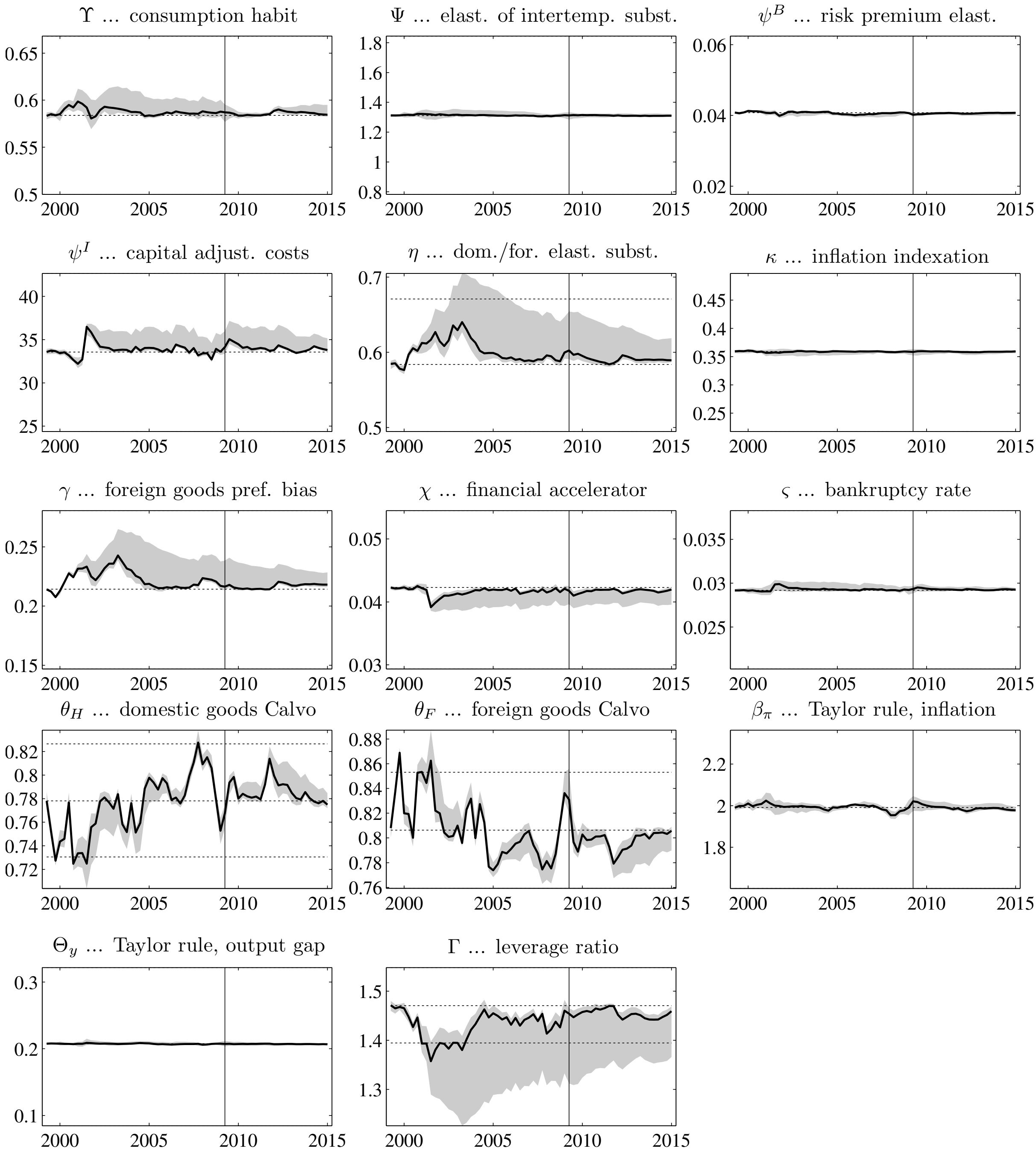
Source: Author, vertical line - 2009Q1.

Figure C.80: Filtered time-varying parameters (95% HPDI bounds), SK



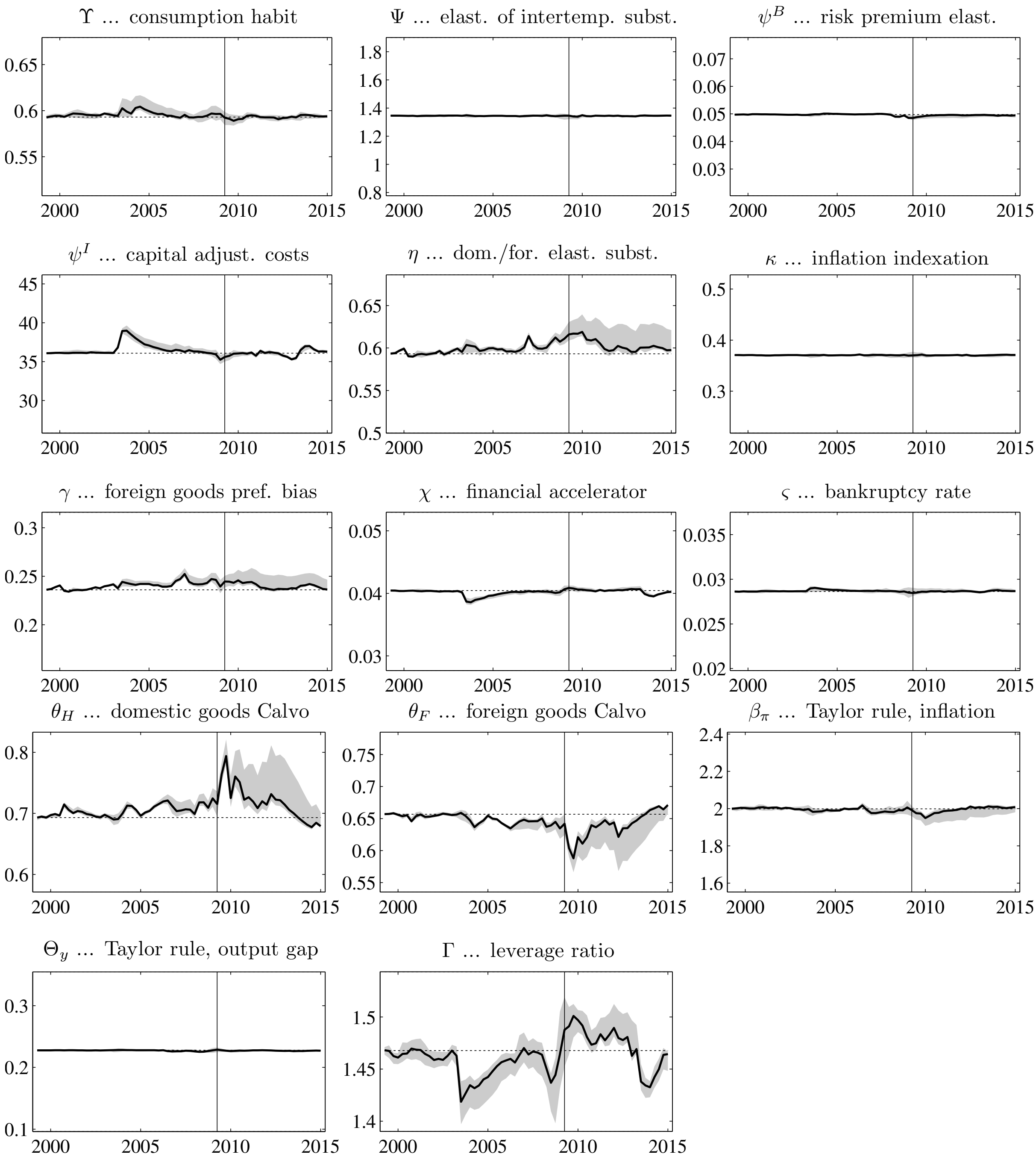
Source: Author, vertical line - 2009Q1.

Figure C.81: Filtered time-varying parameters (95% HPDI bounds), PL



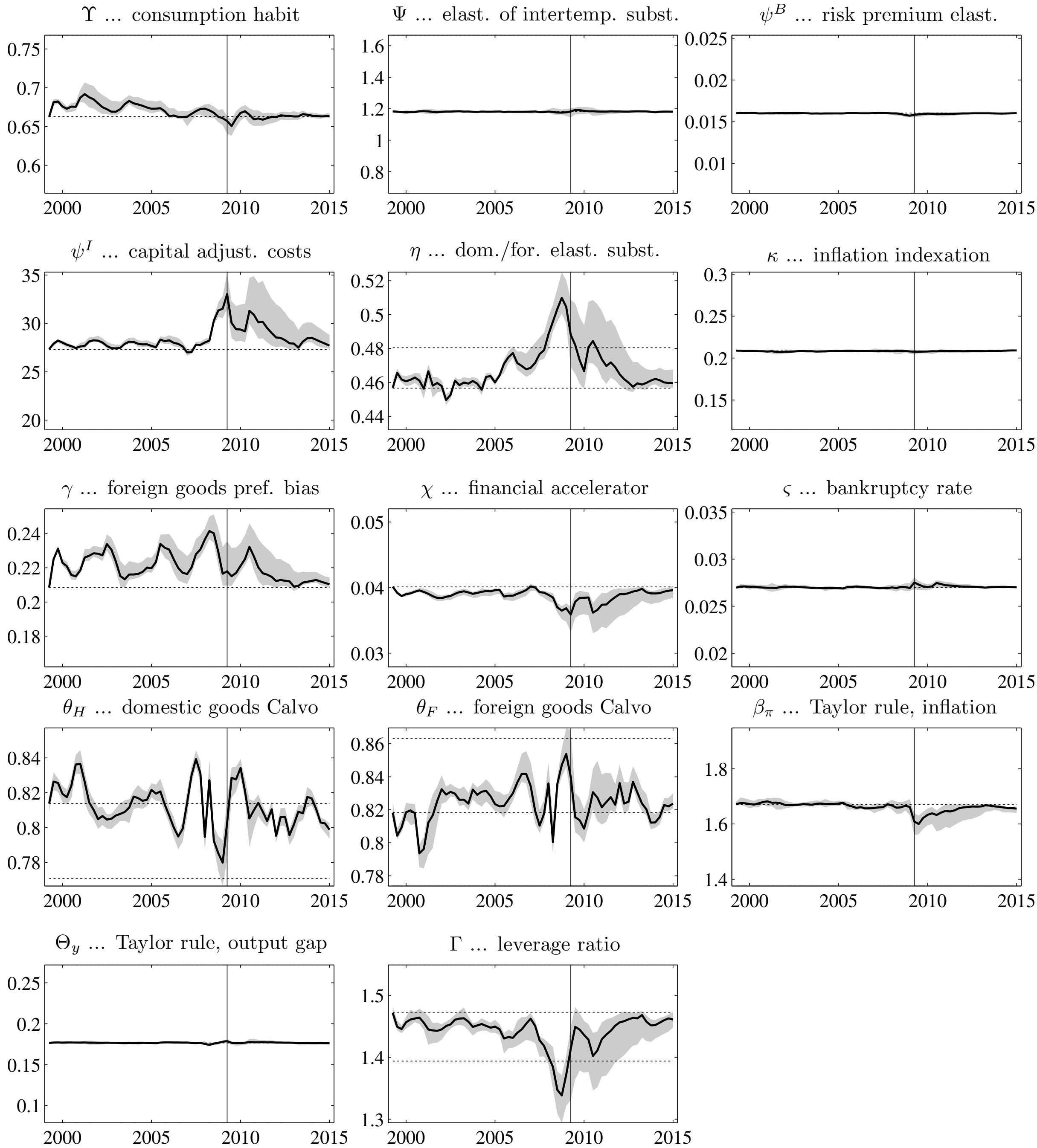
Source: Author, vertical line - 2009Q1.

Figure C.82: Filtered time-varying parameters (95% HPDI bounds), HU



Source: Author, vertical line - 2009Q1.

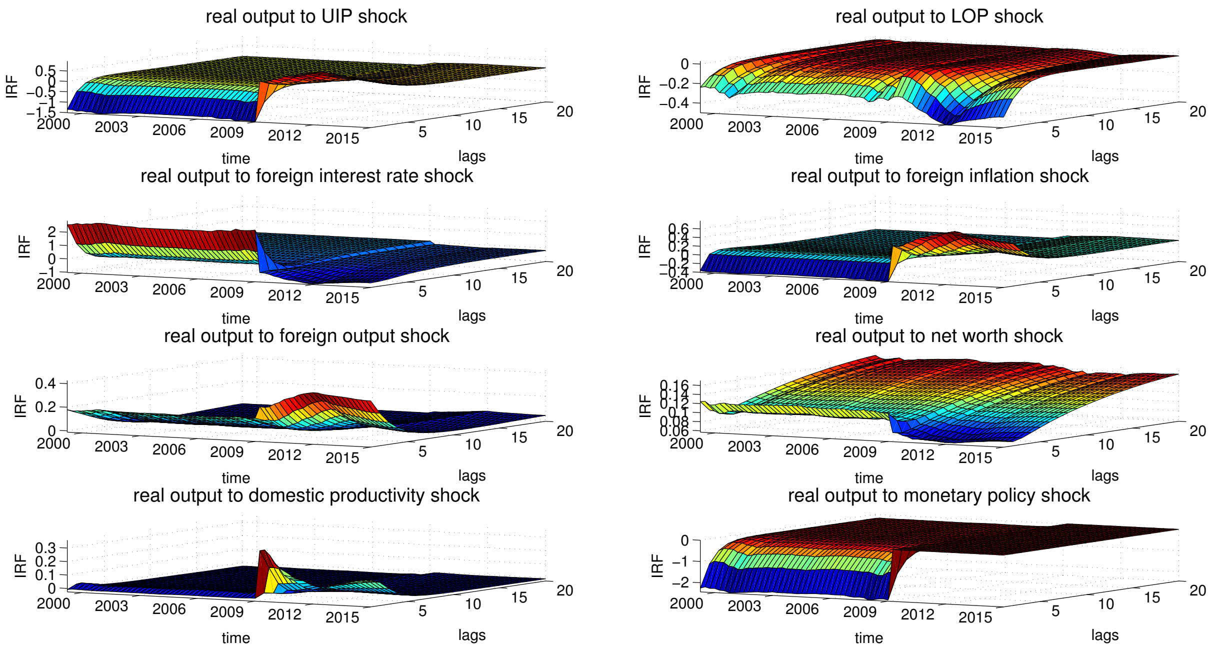
Figure C.83: Filtered time-varying parameters (95% HPDI bounds), EA



Source: Author, vertical line - 2009Q1.

C.8 Time-varying impulse response functions

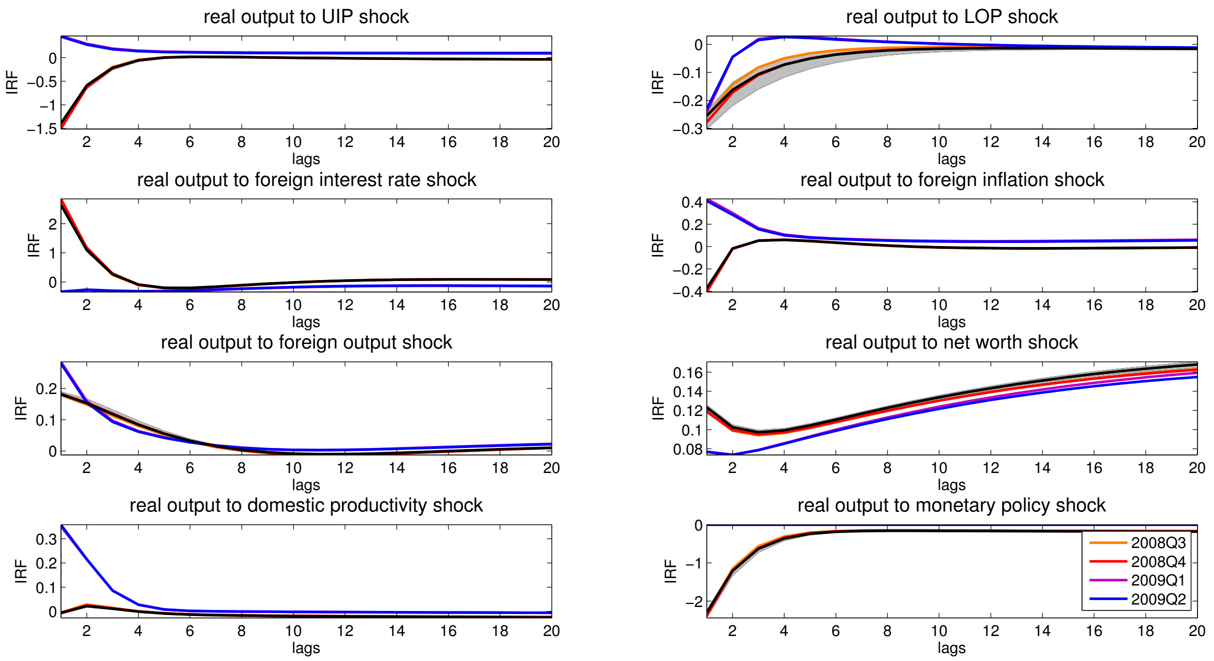
Figure C.84: Time-varying IRFs of real output, constant shocks, SK



Source: Author.

Note: Percentage deviations caused by 1% shocks are depicted.

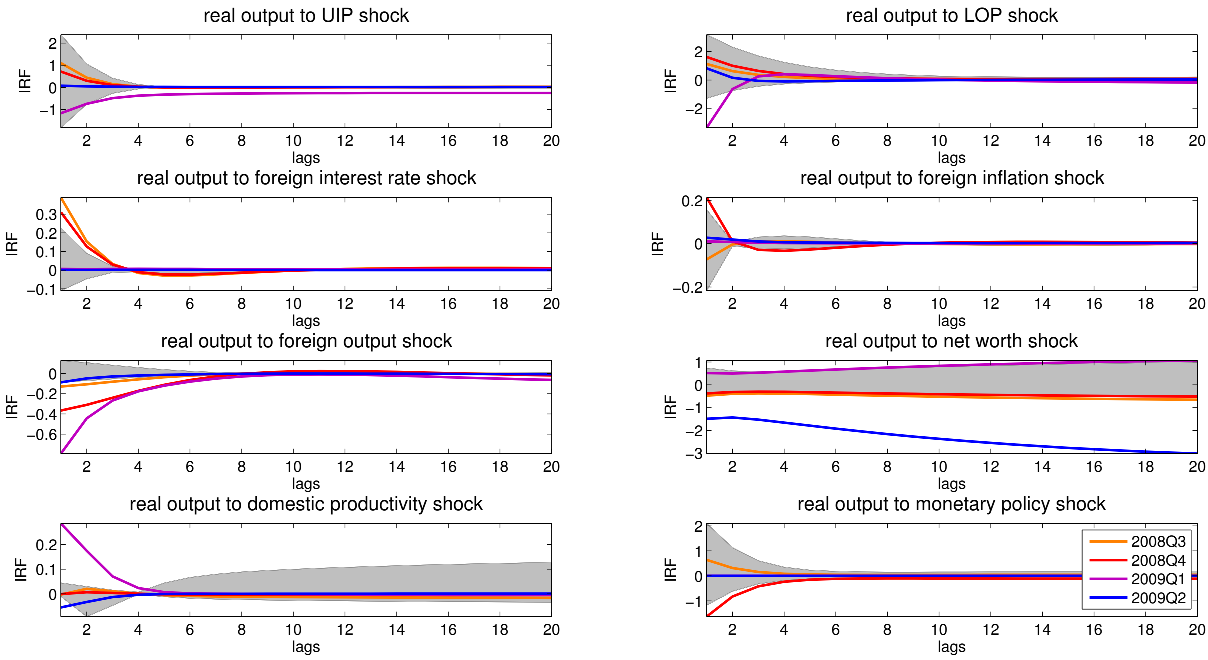
Figure C.85: Time-varying IRFs of real output, constant shocks, projection, SK



Source: Author.

Note: Percentage deviations caused by 1% shocks are depicted, shaded area - pre-crisis period (2003Q3-2008Q2), black line - pre-crisis mean.

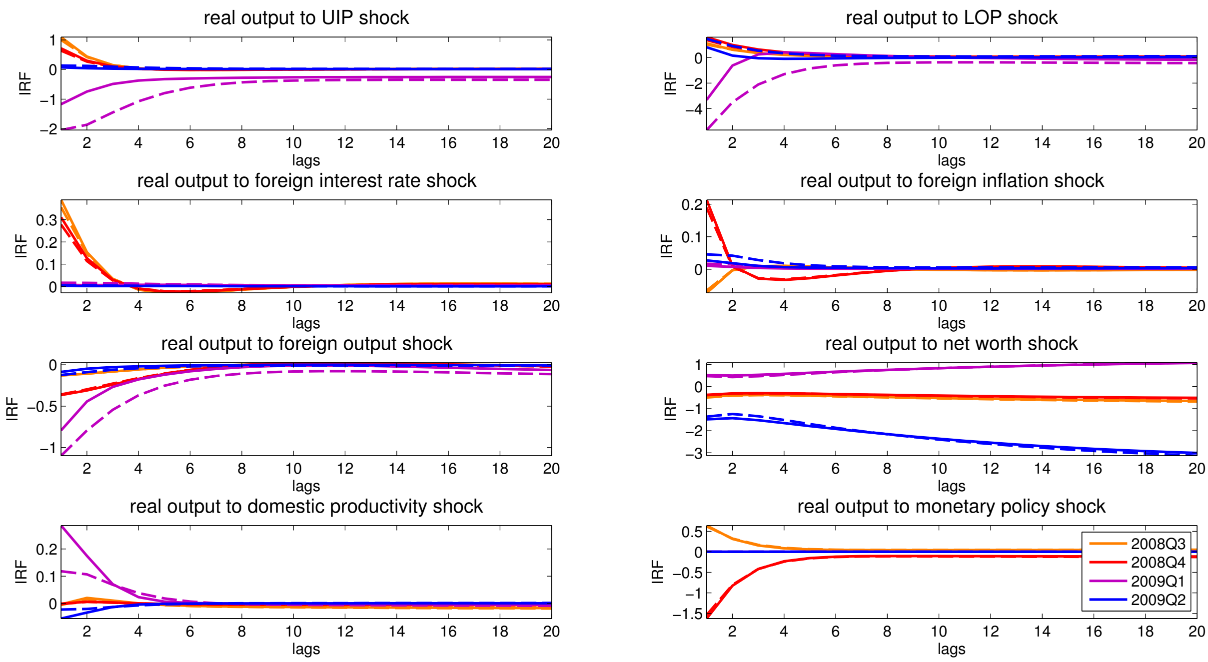
Figure C.86: Time-varying IRFs of real output, historical shocks, SK



Source: Author.

Note: Percentage deviations caused by 1% shocks are depicted, shaded area - pre-crisis period (2003Q3-2008Q2).

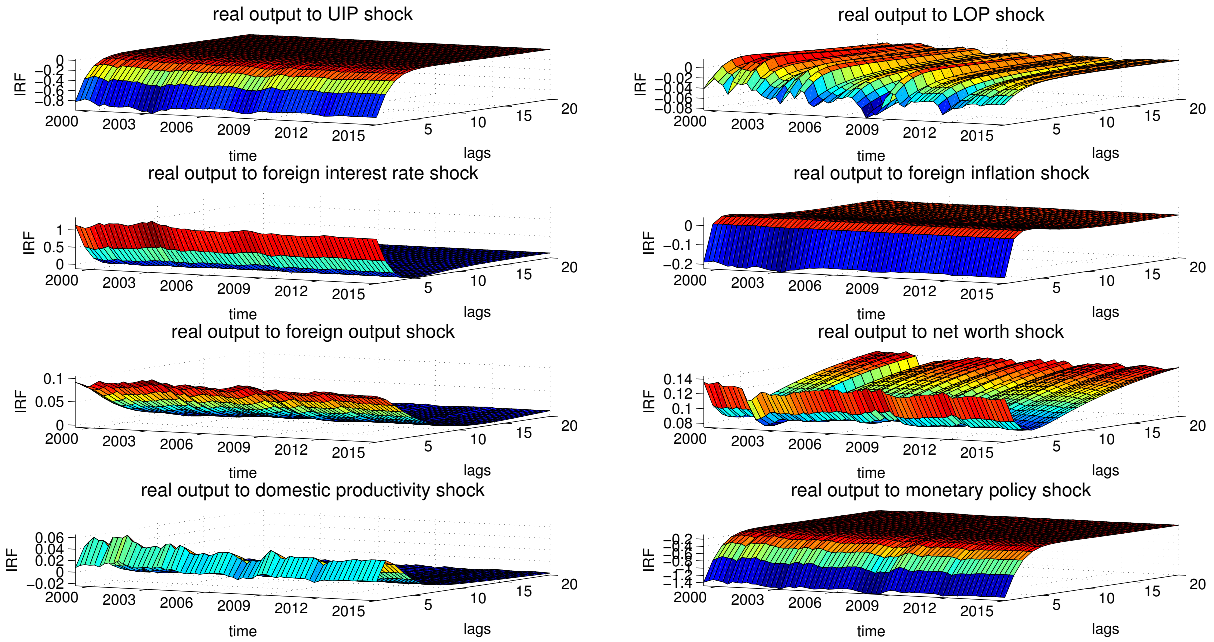
Figure C.87: Time-varying IRFs of real output, historical shocks, comparison, SK



Source: Author.

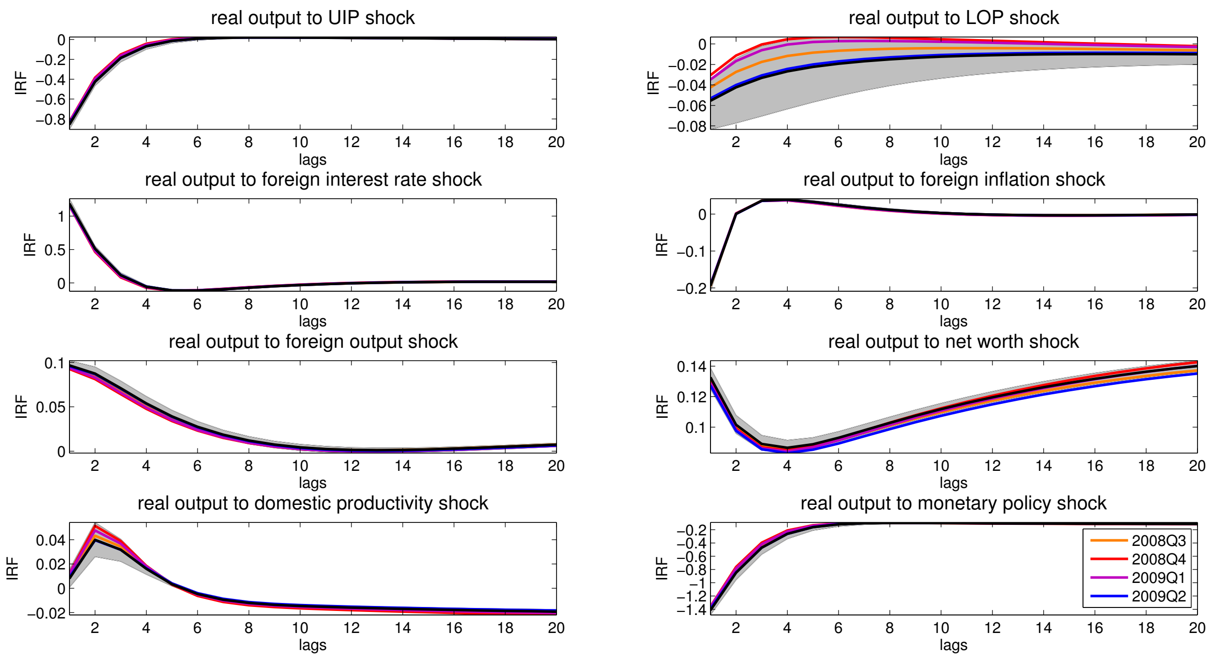
Note: Percentage deviations caused by 1% shocks are depicted, solid lines - time-varying structure, dashed lines - baseline structure.

Figure C.88: Time-varying IRFs of real output, constant shocks, PL



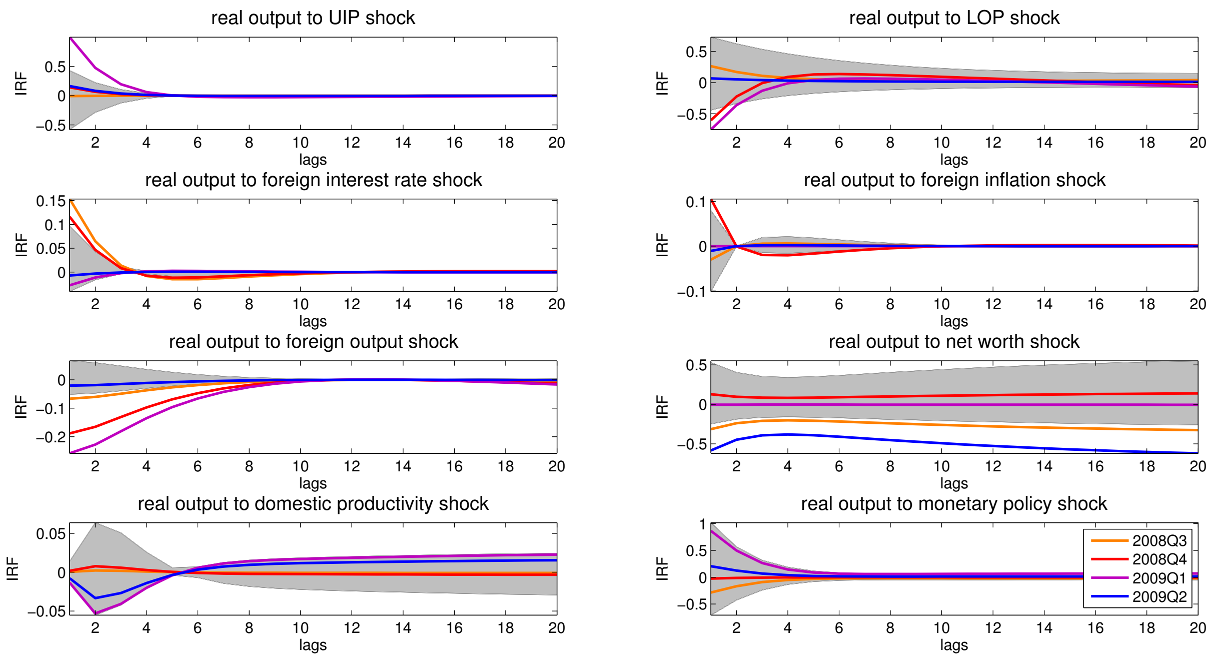
Source: Author.
Note: Percentage deviations caused by 1% shocks are depicted.

Figure C.89: Time-varying IRFs of real output, constant shocks, projection, PL



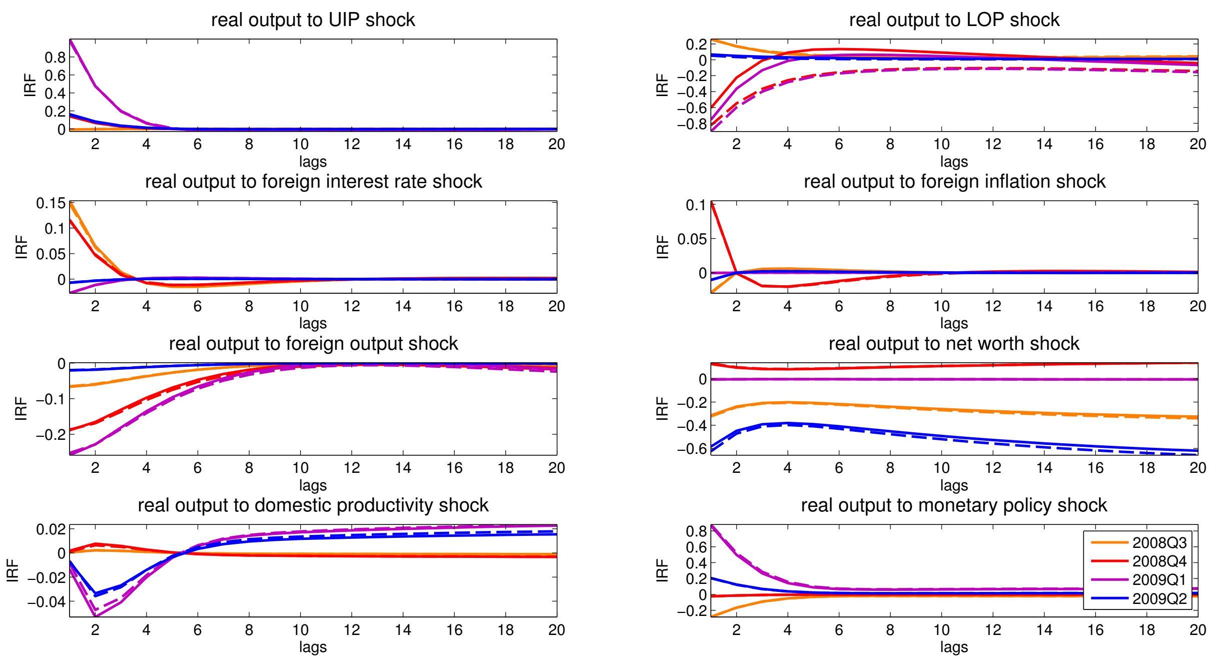
Source: Author.
Note: Percentage deviations caused by 1% shocks are depicted, shaded area - pre-crisis period (2003Q3-2008Q2), , black line - pre-crisis mean.

Figure C.90: Time-varying IRFs of real output, historical shocks, PL



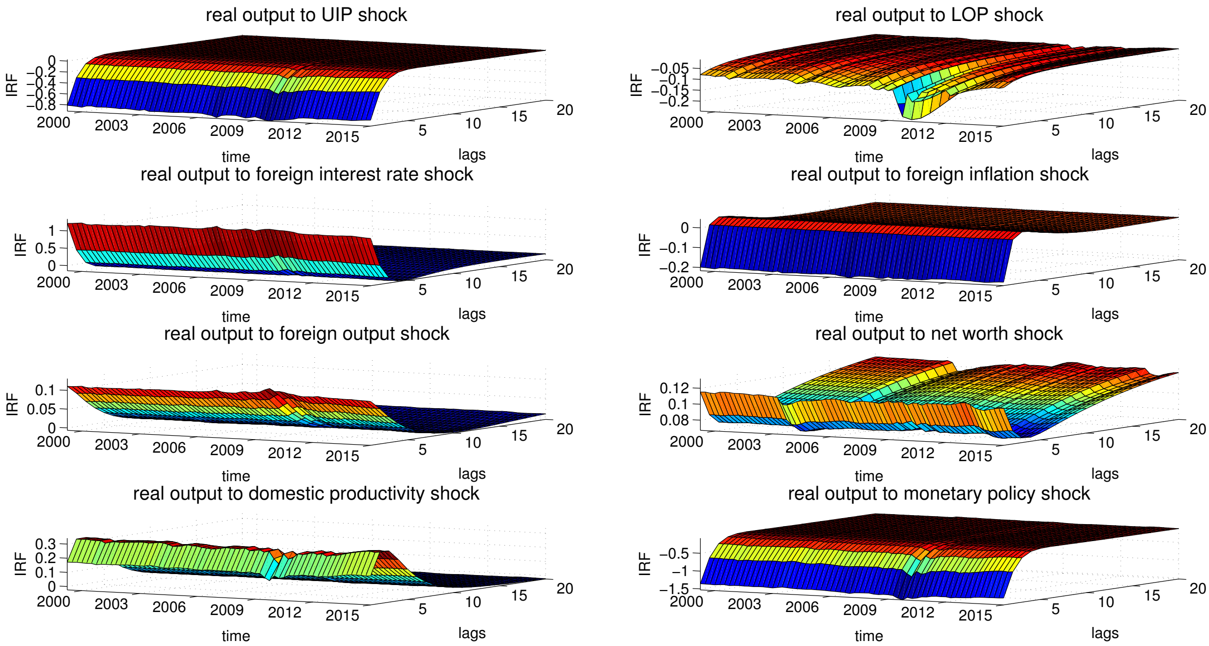
Source: Author.
Note: Percentage deviations caused by 1% shocks are depicted, shaded area - pre-crisis period (2003Q3-2008Q2).

Figure C.91: Time-varying IRFs of real output, historical shocks, comparison, PL



Source: Author.
Note: Percentage deviations caused by 1% shocks are depicted, solid lines - time-varying structure, dashed lines - baseline structure.

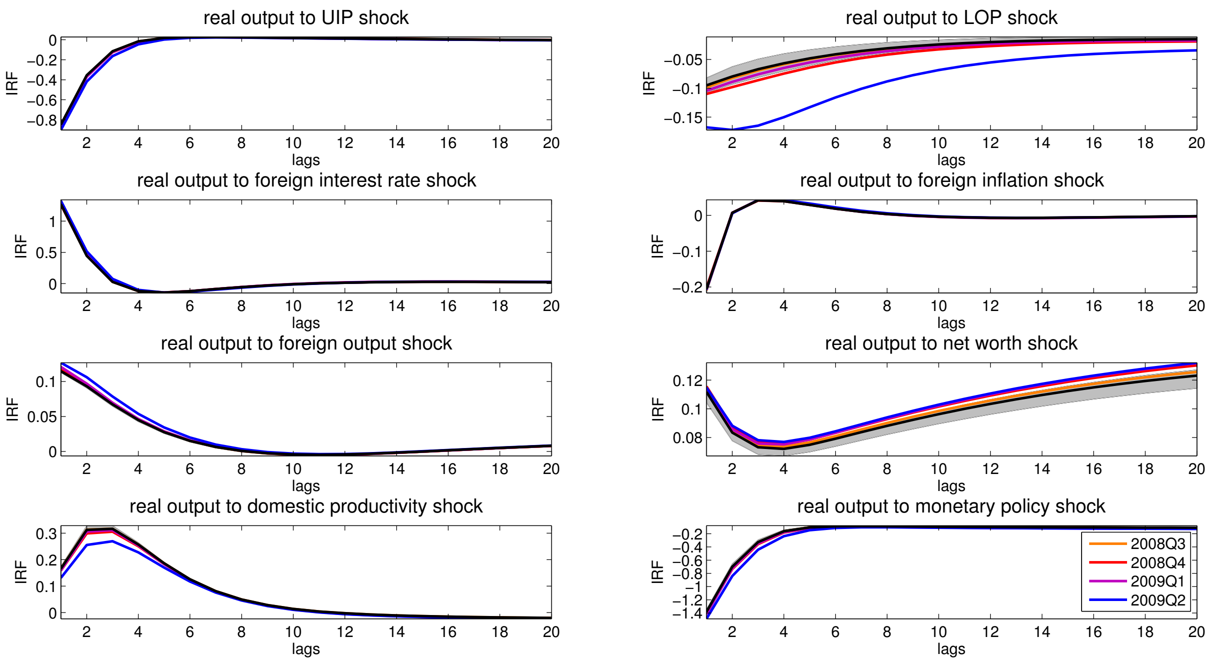
Figure C.92: Time-varying IRFs of real output, constant shocks, HU



Source: Author.

Note: Percentage deviations caused by 1% shocks are depicted.

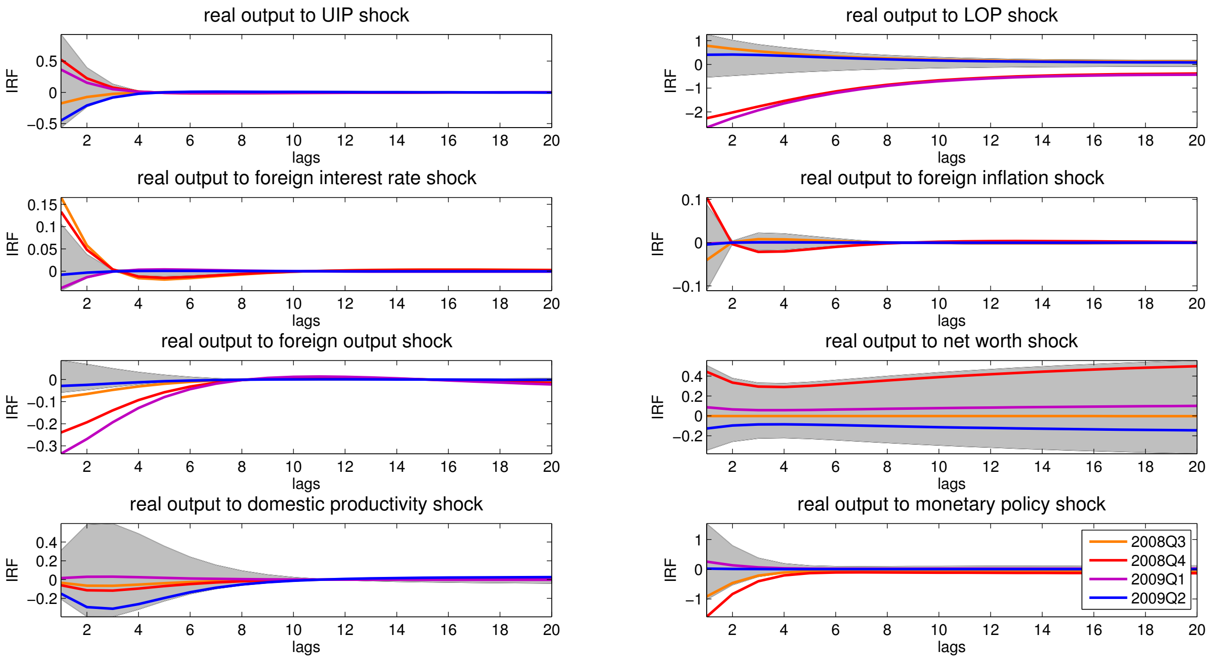
Figure C.93: Time-varying IRFs of real output, constant shocks, projection, HU



Source: Author.

Note: Percentage deviations caused by 1% shocks are depicted, shaded area - pre-crisis period (2003Q3-2008Q2), black line - pre-crisis mean.

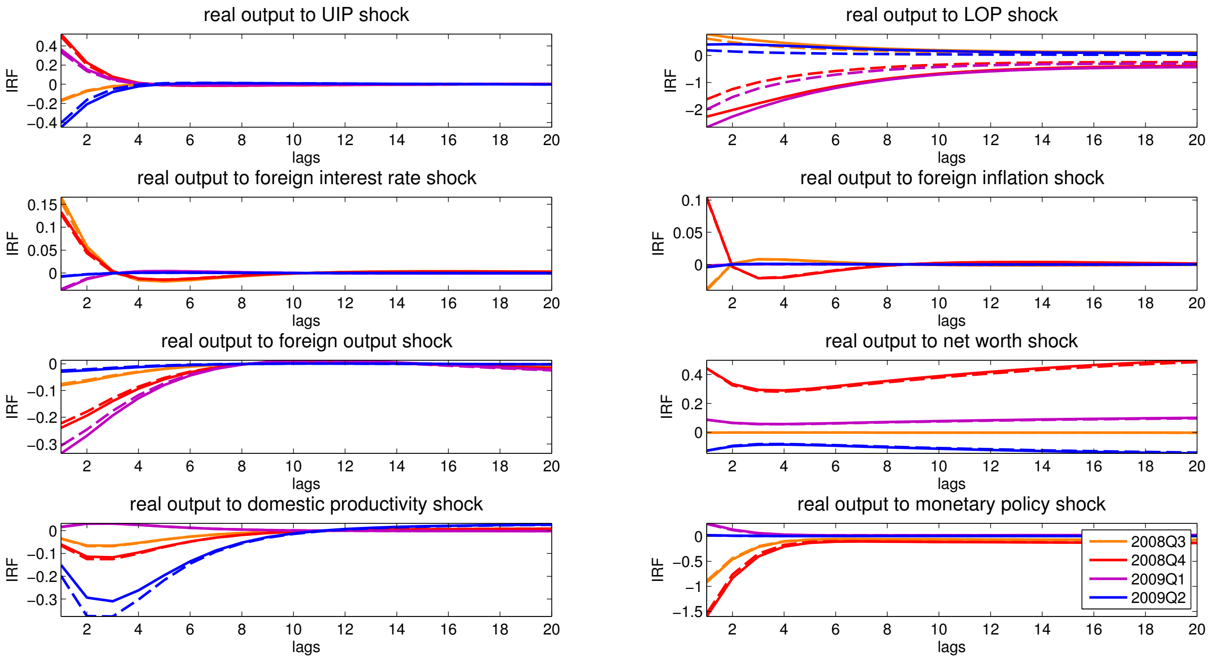
Figure C.94: Time-varying IRFs of real output, historical shocks, HU



Source: Author.

Note: Percentage deviations caused by 1% shocks are depicted, shaded area - pre-crisis period (2003Q3-2008Q2).

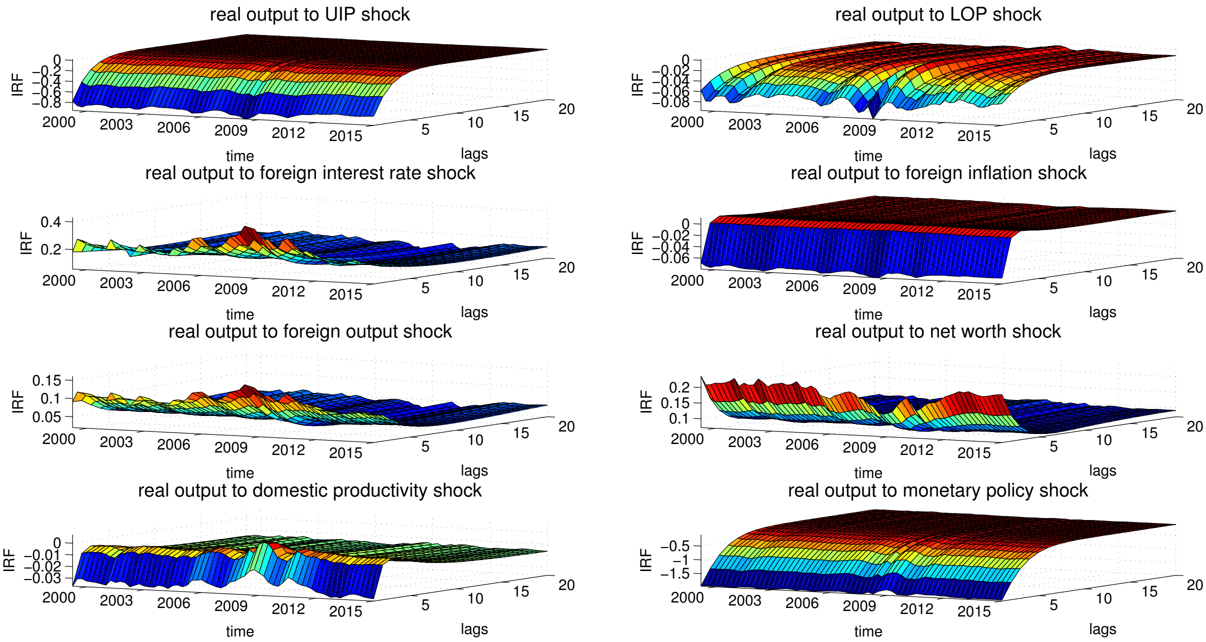
Figure C.95: Time-varying IRFs of real output, historical shocks, comparison, HU



Source: Author.

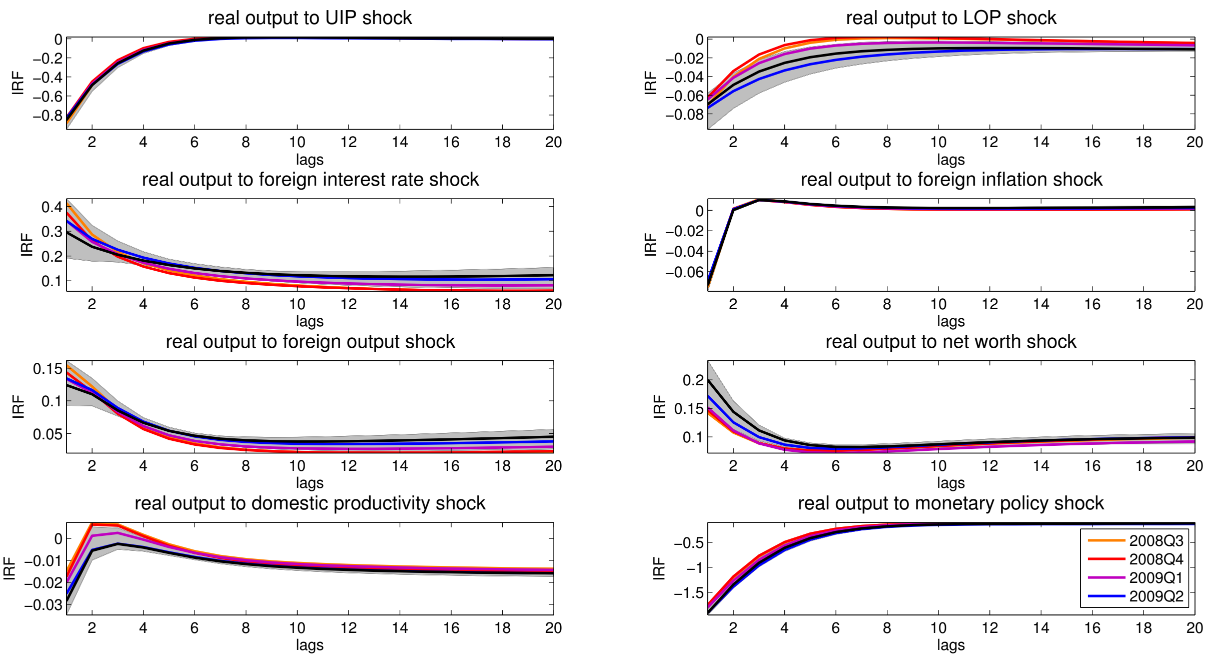
Note: Percentage deviations caused by 1% shocks are depicted, solid lines - time-varying structure, dashed lines - baseline structure.

Figure C.96: Time-varying IRFs of real output, constant shocks, EA



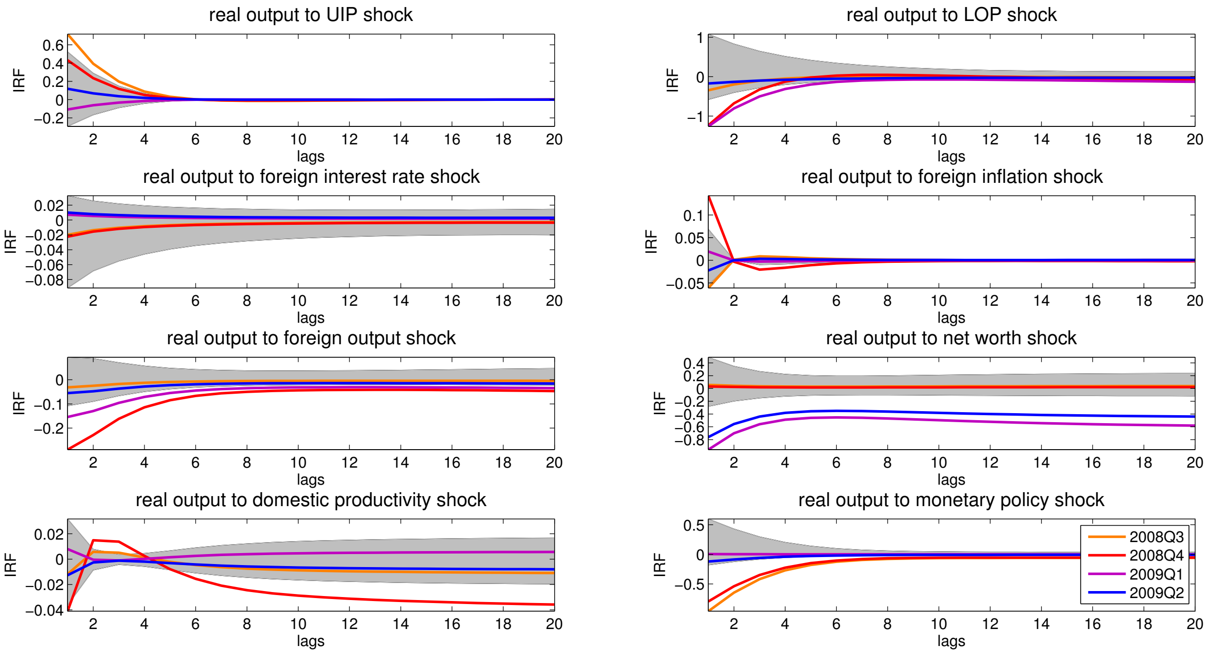
Source: Author.
Note: Percentage deviations caused by 1% shocks are depicted.

Figure C.97: Time-varying IRFs of real output, constant shocks, projection, EA



Source: Author.
Note: Percentage deviations caused by 1% shocks are depicted, shaded area - pre-crisis period (2003Q3-2008Q2), black line - pre-crisis mean.

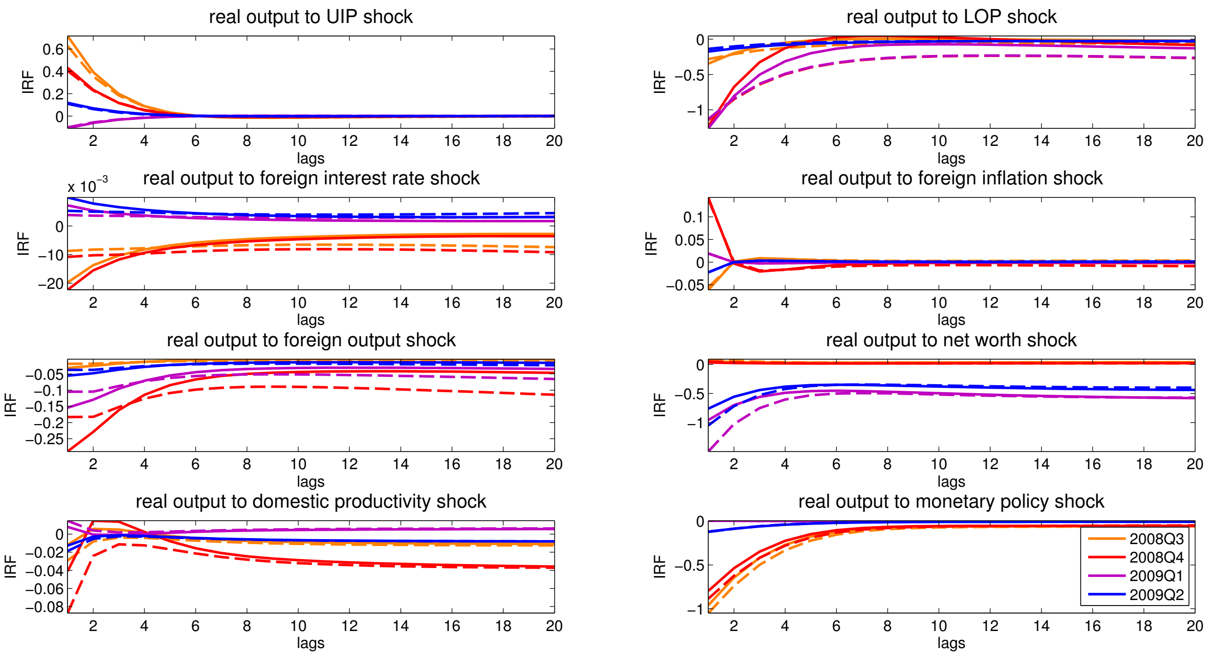
Figure C.98: Time-varying IRFs of real output, historical shocks, EA



Source: Author.

Note: Percentage deviations caused by 1% shocks are depicted, shaded area - pre-crisis period (2003Q3-2008Q2).

Figure C.99: Time-varying IRFs of real output, historical shocks, comparison, EA

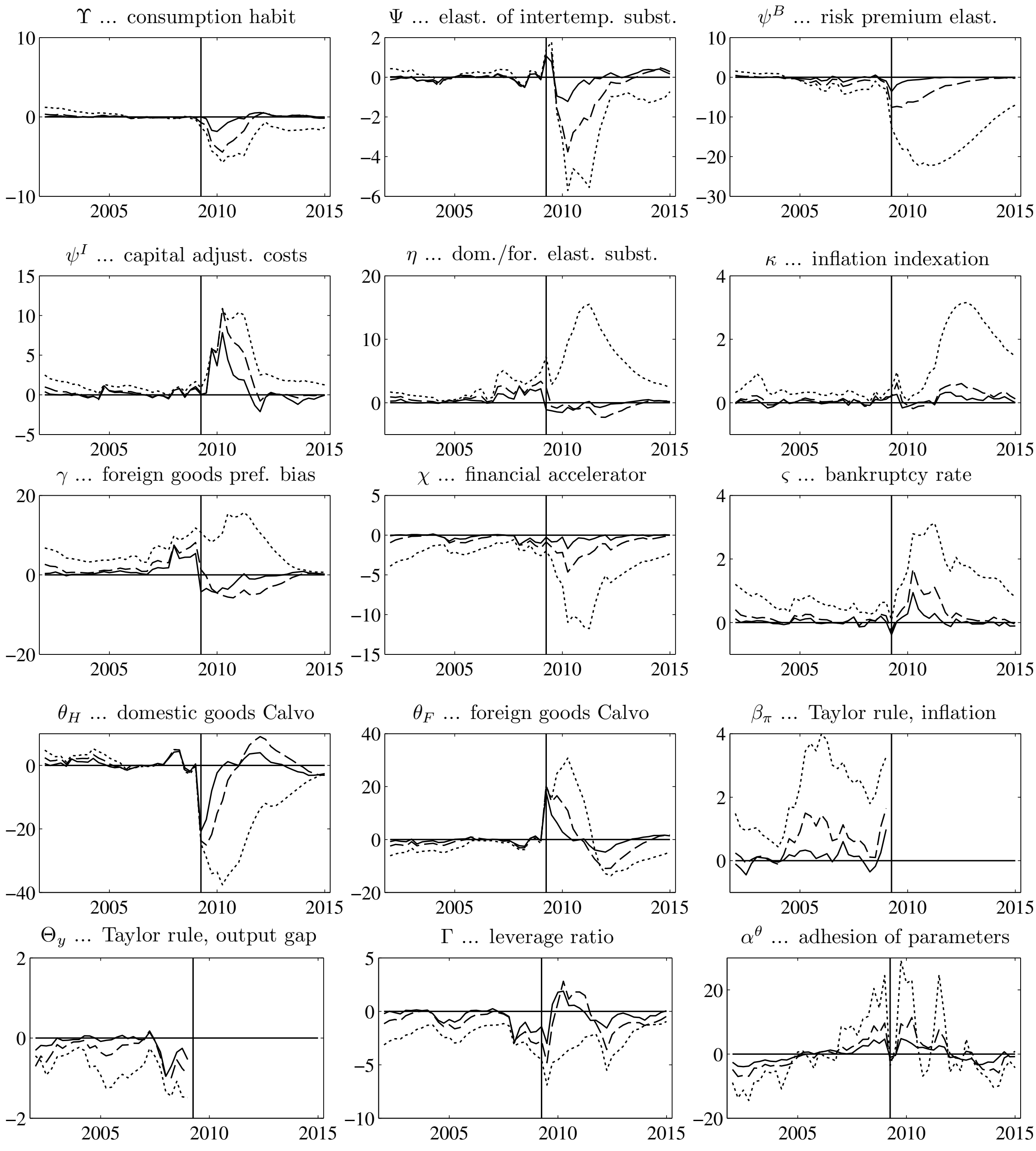


Source: Author.

Note: Percentage deviations caused by 1% shocks are depicted, solid lines - time-varying structure, dashed lines - baseline structure, vertical line - 2009Q1.

C.9 NPF sensitivity to adhesion calibration

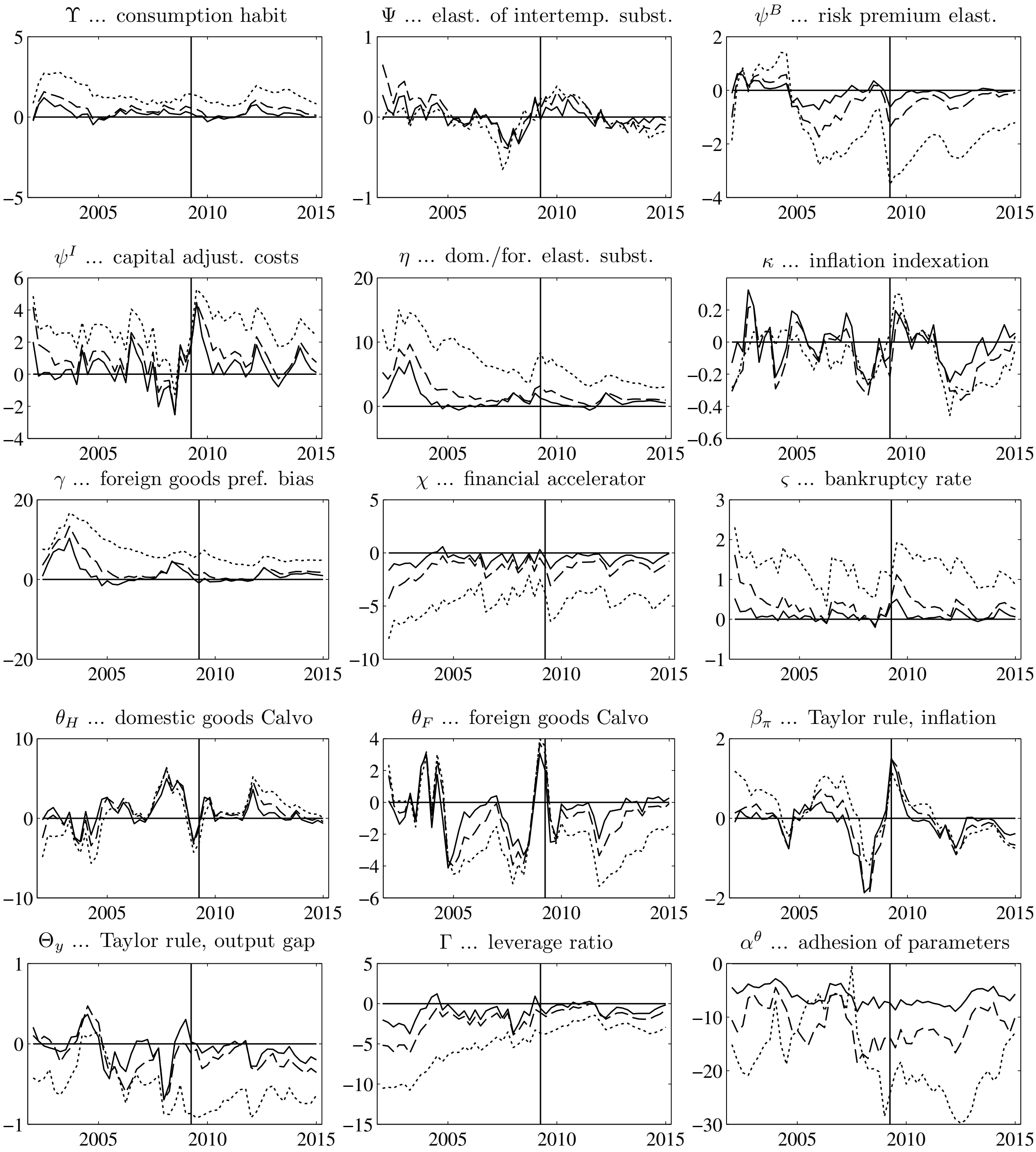
Figure C.100: NPF sensitivity to adhesion parameter calibration, SK



Source: Author.

Note: Percentage deviations from initial values are depicted, solid line - $\alpha_0^\theta = 0.5$*, dashed line -* $\alpha_0^\theta = 0.25$*, dotted line -* $\alpha_0^\theta = 0.10$*, vertical line - 2009Q1.*

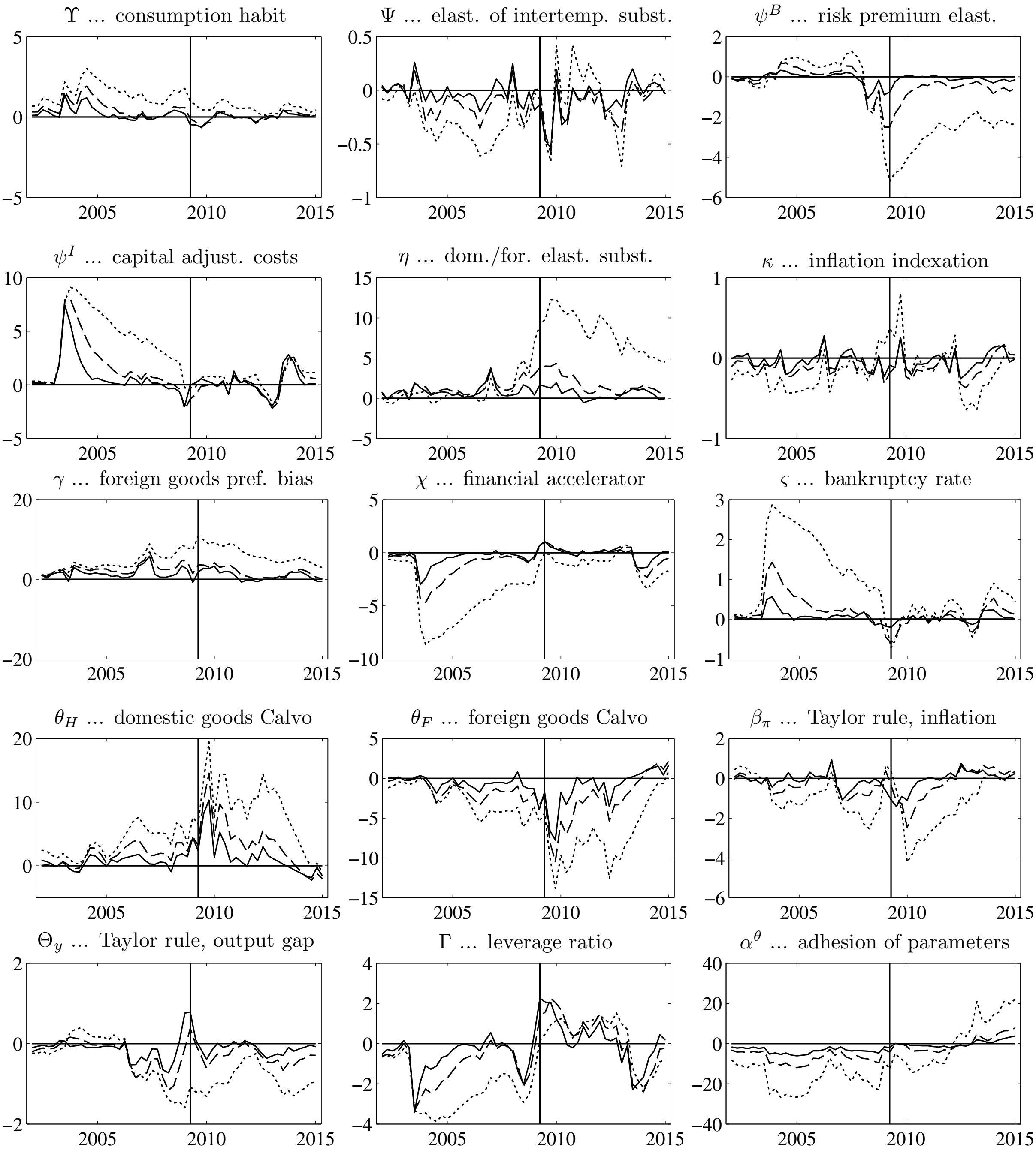
Figure C.101: NPF sensitivity to adhesion parameter calibration, PL



Source: Author.

Note: Percentage deviations from initial values are depicted, solid line - $\alpha_0^\theta = 0.5$*, dashed line -* $\alpha_0^\theta = 0.25$*, dotted line -* $\alpha_0^\theta = 0.10$*, vertical line - 2009Q1.*

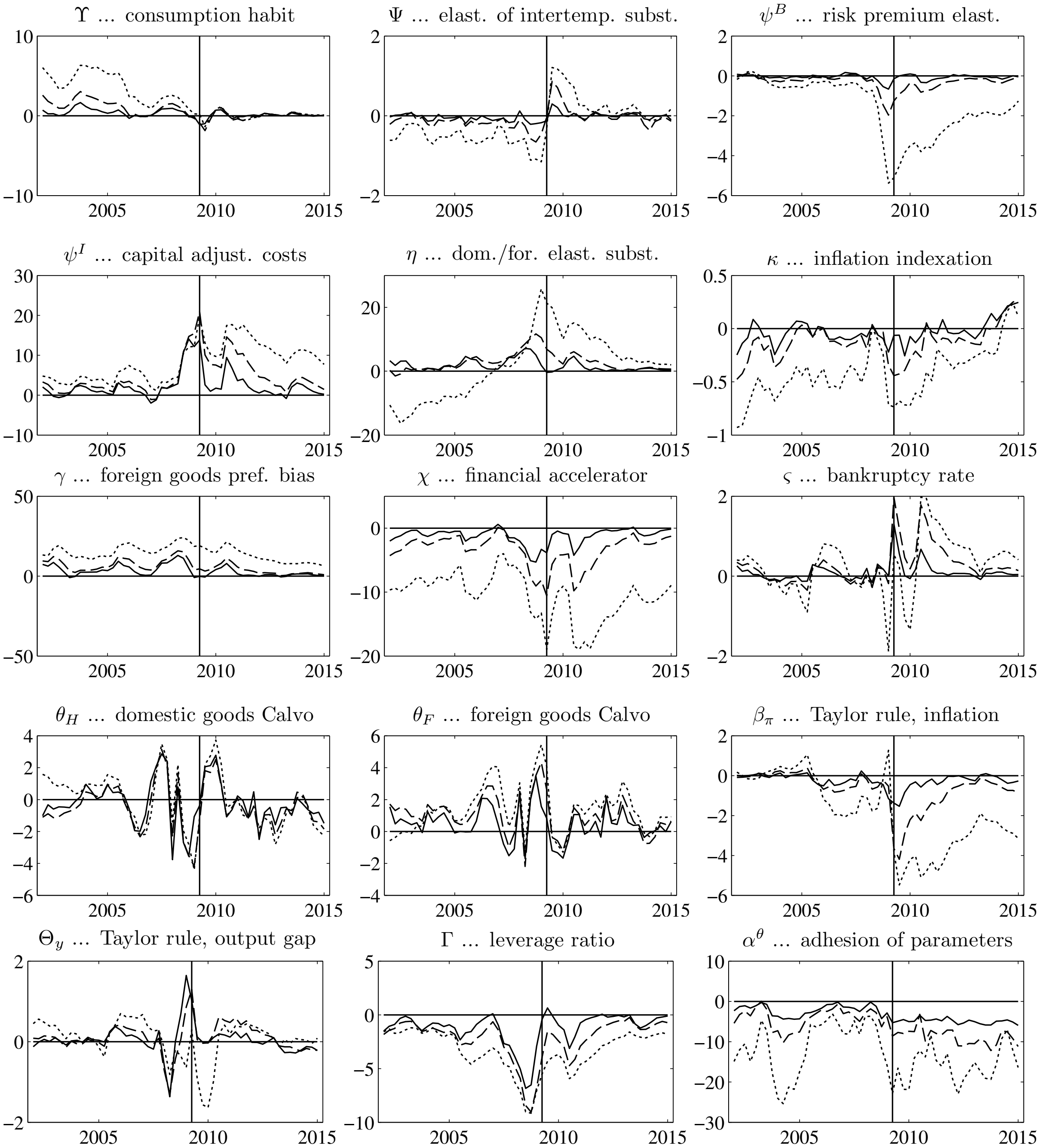
Figure C.102: NPF sensitivity to adhesion parameter calibration, HU



Source: Author.

Note: Percentage deviations from initial values are depicted, solid line - $\alpha_0^\theta = 0.5$*, dashed line -* $\alpha_0^\theta = 0.25$*, dotted line -* $\alpha_0^\theta = 0.10$*, vertical line - 2009Q1.*

Figure C.103: NPF sensitivity to adhesion parameter calibration, EA

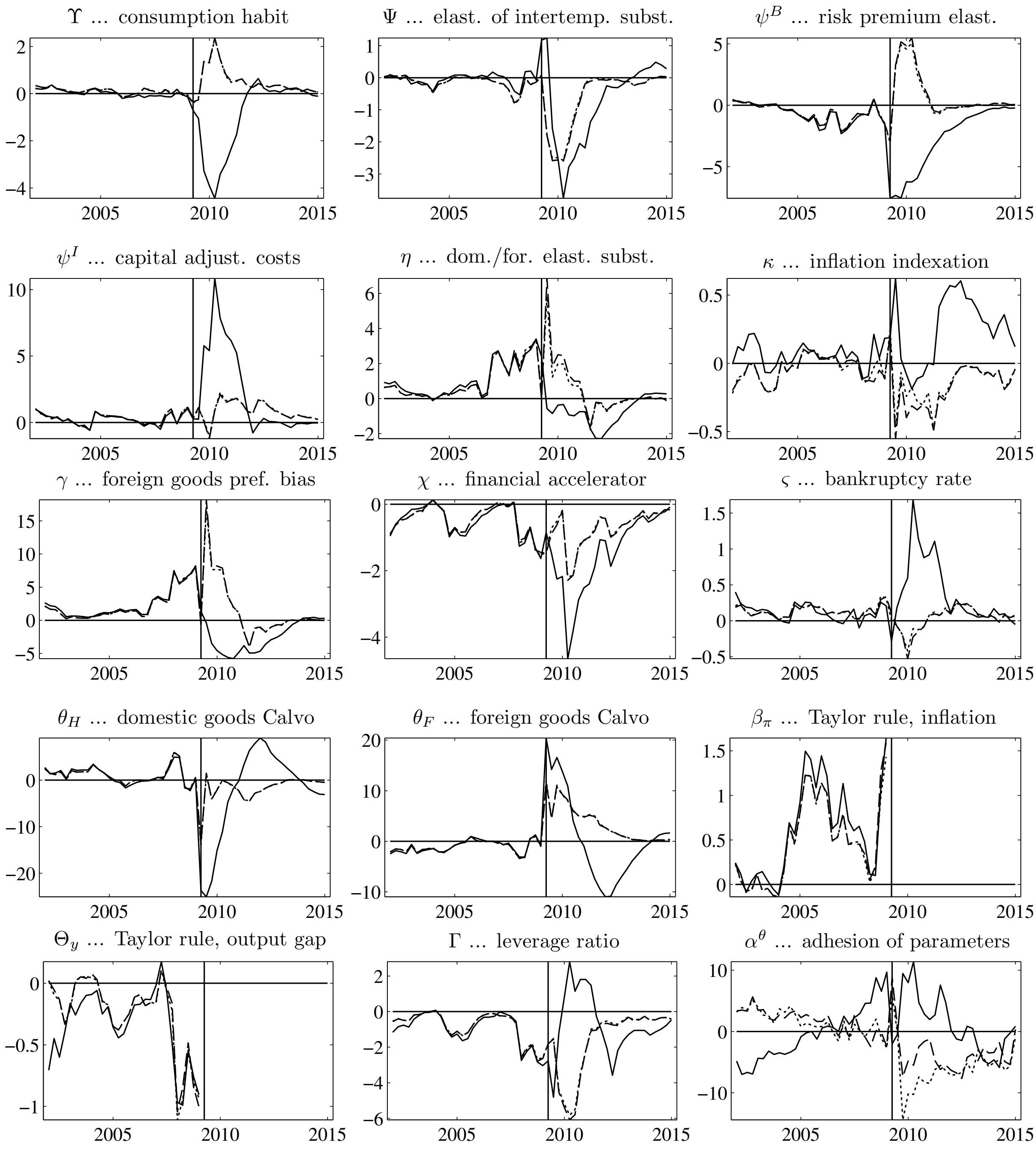


Source: Author.

Note: Percentage deviations from initial values are depicted, solid line - $\alpha_0^\theta = 0.5$*, dashed line -* $\alpha_0^\theta = 0.25$*, dotted line -* $\alpha_0^\theta = 0.10$*, vertical line - 2009Q1.*

C.10 NPF sensitivity to parameters selection

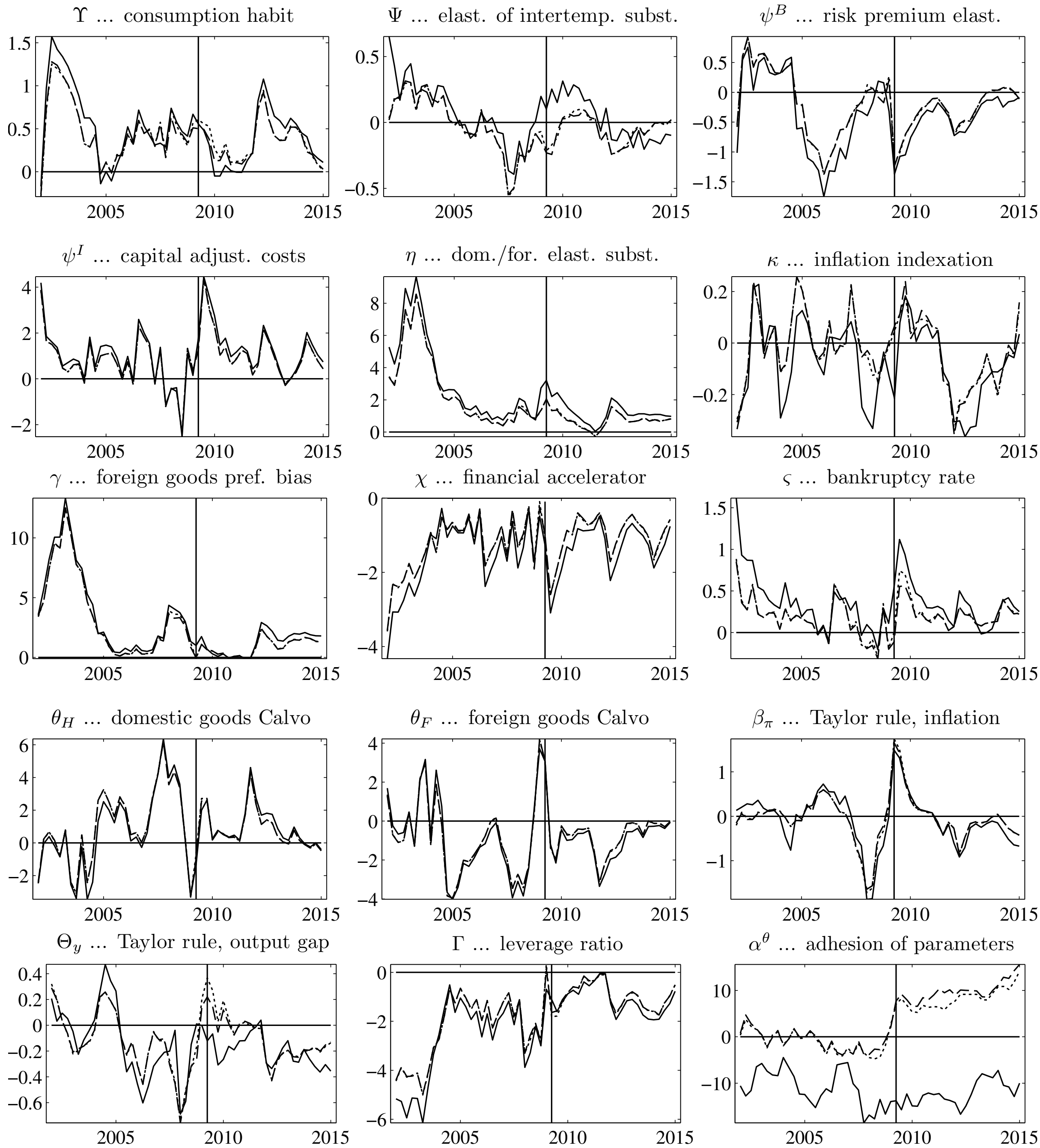
Figure C.104: NPF sensitivity to time-varying parameters selection, SK



Source: Author.

Note: Percentage deviations from initial values are depicted, solid line - structural parameters, dashed line - structural parameters + AR, dotted line - structural parameters + AR + SVAR, vertical line - 2009Q1.

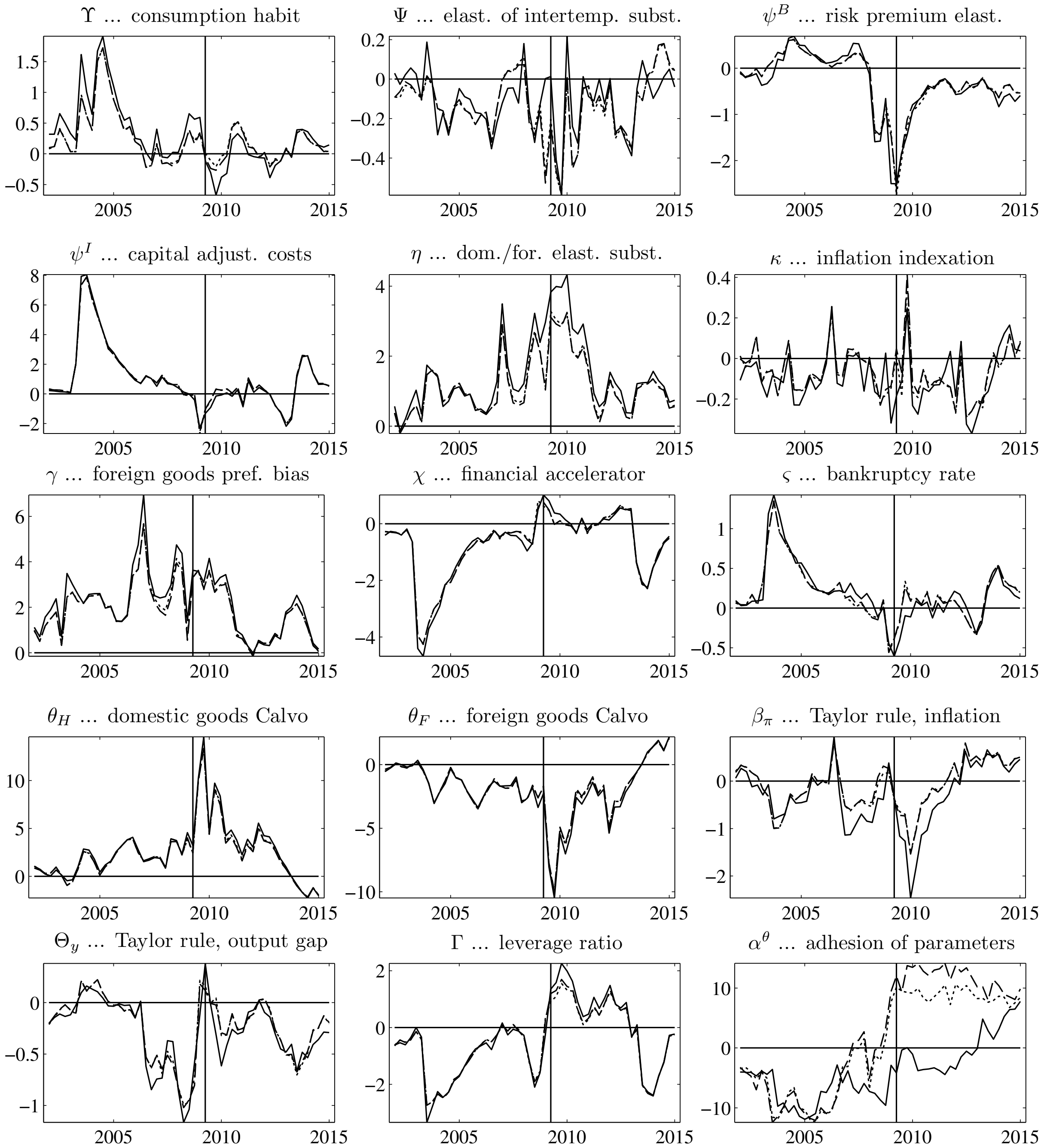
Figure C.105: NPF sensitivity to time-varying parameters selection, PL



Source: Author.

Note: Percentage deviations from initial values are depicted, solid line - structural parameters, dashed line - structural parameters + AR, dotted line - structural parameters + AR + SVAR, vertical line - 2009Q1.

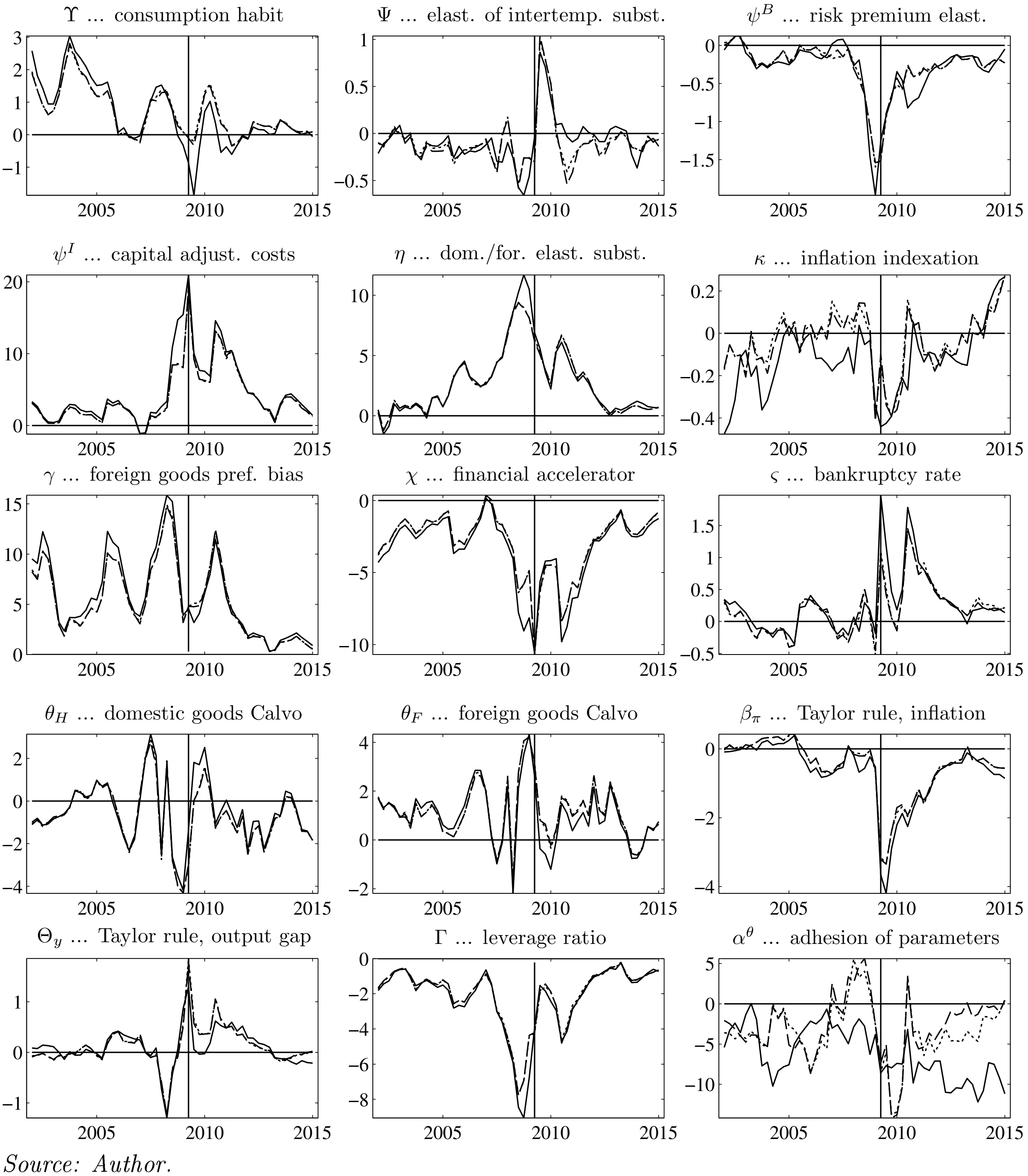
Figure C.106: NPF sensitivity to time-varying parameters selection, HU



Source: Author.

Note: Percentage deviations from initial values are depicted, solid line - structural parameters, dashed line - structural parameters + AR, dotted line - structural parameters + AR + SVAR, vertical line - 2009Q1.

Figure C.107: NPF sensitivity to time-varying parameters selection, EA

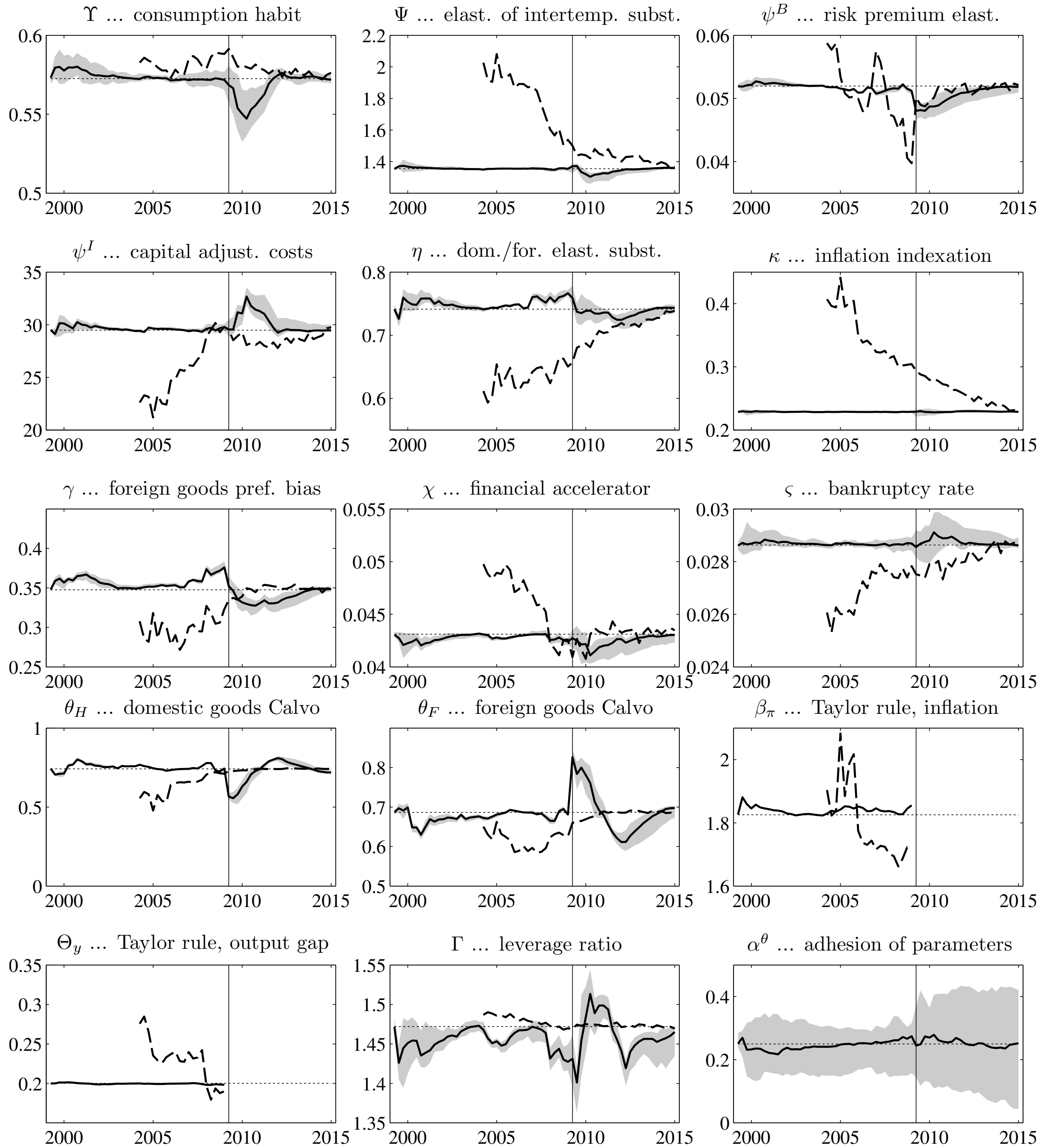


Source: Author.

Note: Percentage deviations from initial values are depicted, solid line - structural parameters, dashed line - structural parameters + AR, dotted line - structural parameters + AR + SVAR, vertical line - 2009Q1.

C.11 Comparison of NPF and recursive estimates

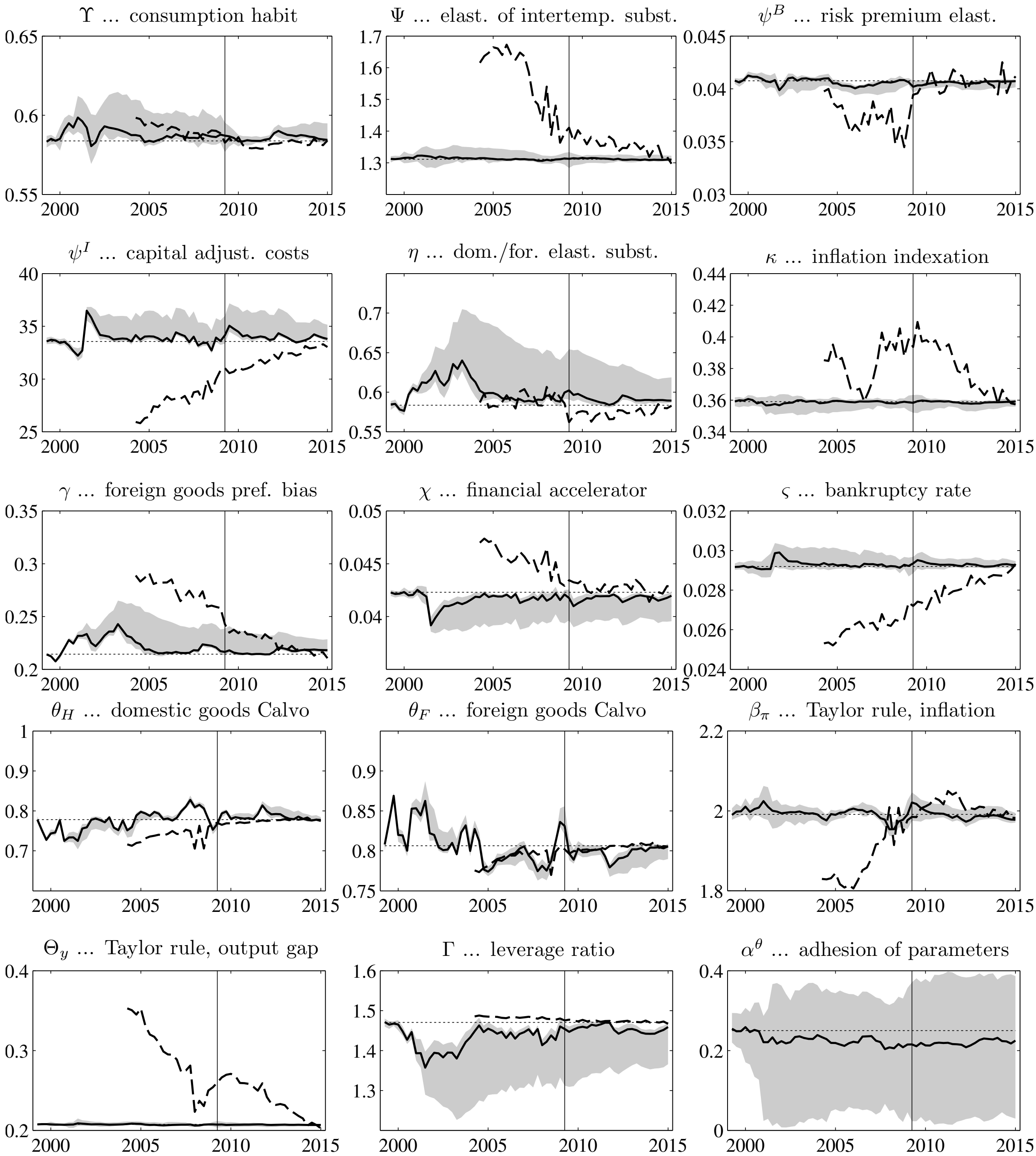
Figure C.108: NPF vs. recursive estimation, SK



Source: Author.

Note: Solid line - NPF estimates, dashed line - recursive estimates, vertical line - 2009Q1.

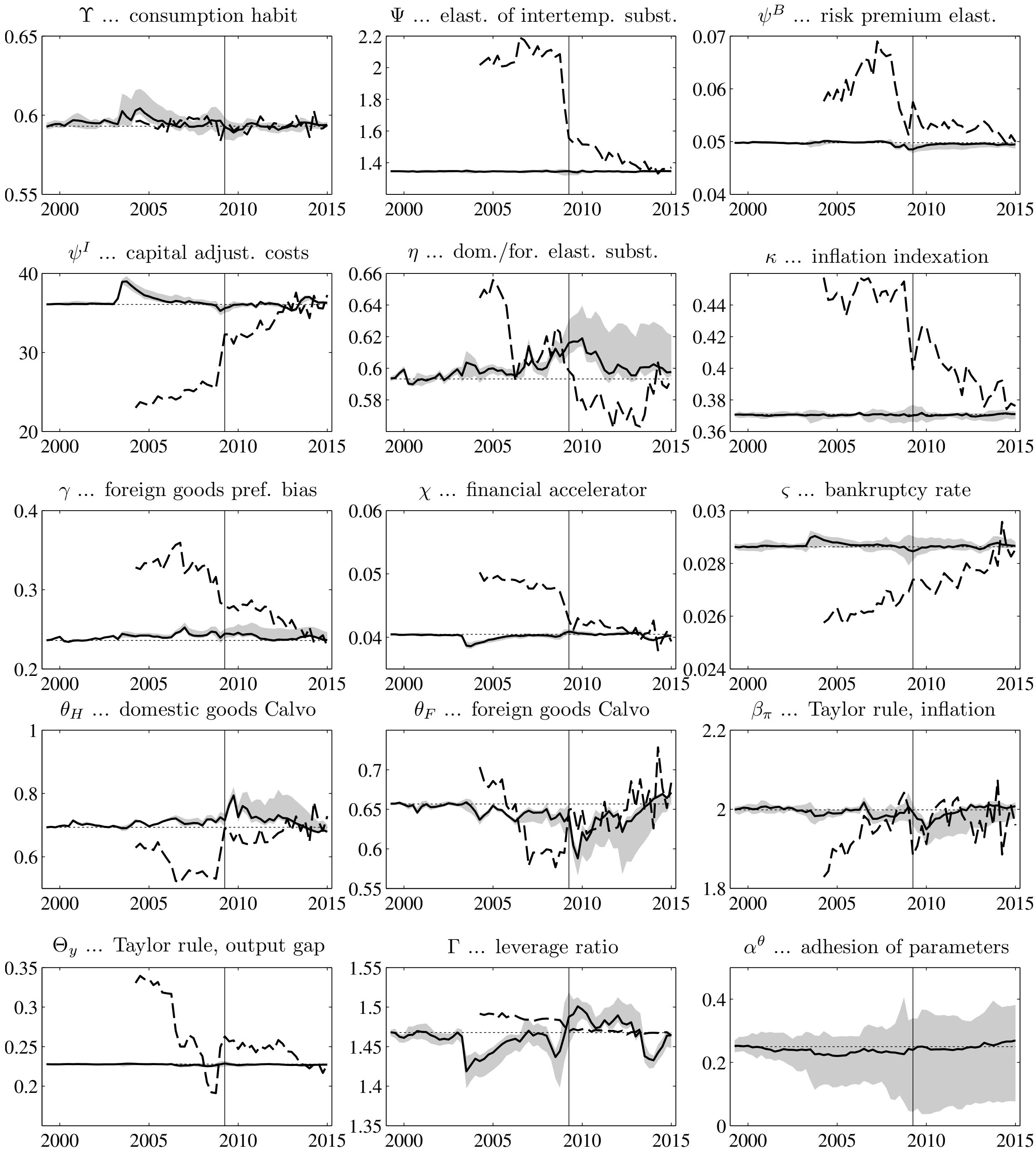
Figure C.109: NPF vs. recursive estimation, PL



Source: Author.

Note: Solid line - NPF estimates, dashed line - recursive estimates, vertical line - 2009Q1.

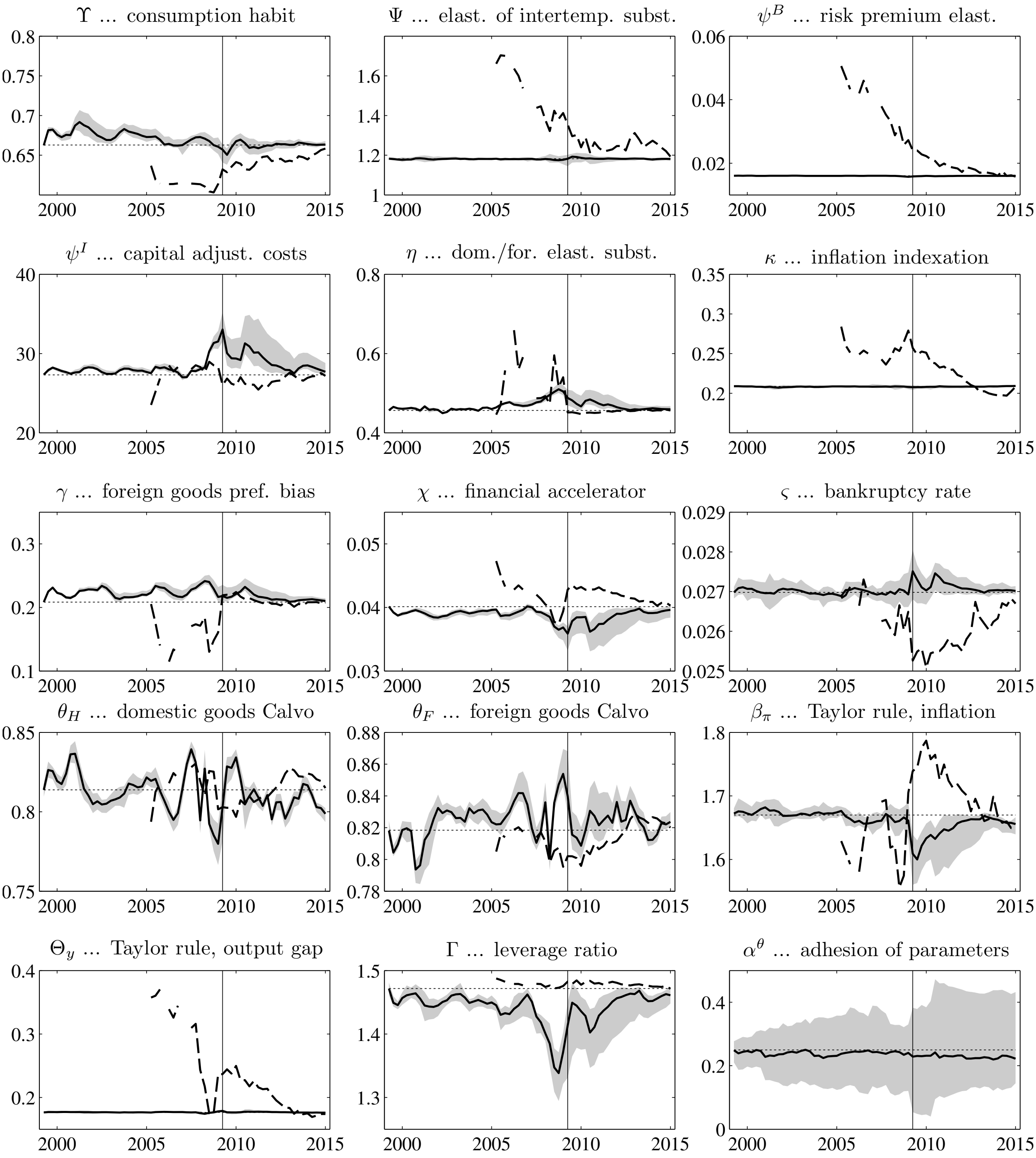
Figure C.110: NPF vs. recursive estimation, HU



Source: Author.

Note: Solid line - NPF estimates, dashed line - recursive estimates, vertical line - 2009Q1.

Figure C.111: NPF vs. recursive estimation, EA



Source: Author.

Note: Solid line - NPF estimates, dashed line - recursive estimates, vertical line - 2009Q1.

Appendix D

Tables

Table D.1: Estimated parameters (CZ model)

Parameter		Distribution	Prior		Posterior		
			Mean	**Std**	**Mean**	**95% HPDI**	
Υ	habit persistence	Beta	0.60	0.05	0.59	0.51	0.68
Ψ	inverse elasticity of labour supply	Gamma	2.00	0.50	1.24	0.72	1.75
ψ^B	elasticity of debt-elastic risk premium	Gamma	0.05	0.02	0.02	0.01	0.03
η	home and foreign goods elasticity of substitution	Gamma	0.65	0.10	0.60	0.48	0.71
κ	price indexation	Beta	0.50	0.10	0.27	0.16	0.38
γ	preference bias to foreign goods	Beta	0.40	0.10	0.29	0.20	0.39
θ_H	home goods Calvo parameter	Beta	0.70	0.10	0.81	0.77	0.85
θ_F	foreign goods Calvo parameter	Beta	0.70	0.10	0.79	0.74	0.85
ψ^I	capital adjustment costs	Gamma	20.00	5.00	29.80	21.02	38.04
Γ	steady-state capital net worth ratio	Shifted Gamma	1.50	0.05	1.47	1.39	1.54
ς	entrepreneurs' bankruptcy rate	Beta	0.025	0.005	0.031	0.022	0.041
χ	financial accelerator	Gamma	0.050	0.010	0.038	0.026	0.049
Taylor rule							
ρ	interest rate smoothing	Beta	0.50	0.20	0.86	0.83	0.90
β_π	inflation weight	Shifted Gamma	1.50	0.20	1.94	1.54	2.31
Θ_y	output gap weight	Gamma	0.50	0.20	0.12	0.05	0.18
AR parameters							
ρ_{UIP}	debt-elastic risk premium	Beta	0.50	0.20	0.69	0.57	0.81
ρ_{LOP}	law of one price gap	Beta	0.50	0.20	0.86	0.80	0.91
ρ_{NW}	entrepreneurs' net worth	Beta	0.50	0.20	0.54	0.27	0.82
ρ_Y	domestic productivity	Beta	0.50	0.20	0.10	0.01	0.18
VAR parameters							
$\rho_{y^*y^*}$	interaction of y_t^* and y_{t-1}^*	Beta	0.80	0.10	0.90	0.82	0.98
$\rho_{\pi^*\pi^*}$	interaction of π_t^* and π_{t-1}^*	Beta	0.20	0.05	0.20	0.13	0.28
$\rho_{r^*r^*}$	interaction of r_t^* and r_{t-1}^*	Beta	0.60	0.20	0.60	0.45	0.74
$\rho_{y^*\pi^*}$	interaction of y_t^* and π_{t-1}^*	Normal	0.00	0.50	0.51	0.16	0.86
$\rho_{y^*r^*}$	interaction of y_t^* and r_{t-1}^*	Normal	0.00	0.50	-0.49	-1.05	0.10
$\rho_{\pi^*y^*}$	interaction of π_t^* and y_{t-1}^*	Normal	0.00	0.50	0.18	0.11	0.25
$\rho_{\pi^*r^*}$	interaction of π_t^* and r_{t-1}^*	Normal	0.00	0.50	-0.74	-1.17	-0.32
$\rho_{r^*y^*}$	interaction of r_t^* and y_{t-1}^*	Normal	0.00	0.50	0.05	0.03	0.08
$\rho_{r^*\pi^*}$	interaction of r_t^* and π_{t-1}^*	Normal	0.00	0.50	0.04	-0.02	0.11
$\sigma_{\pi^*y^*}$	interaction of $\varepsilon_t^{\pi^*}$ and $\varepsilon_t^{y^*}$	Normal	0.50	0.25	0.14	0.04	0.24
$\sigma_{r^*y^*}$	interaction of $\varepsilon_t^{r^*}$ and $\varepsilon_t^{y^*}$	Normal	0.30	0.15	0.10	0.07	0.12
$\sigma_{r^*\pi^*}$	interaction of $\varepsilon_t^{r^*}$ and $\varepsilon_t^{\pi^*}$	Normal	0.00	0.50	-0.05	-0.10	0.00
Std of shocks							
σ_{UIP}	debt-elastic risk premium	Inverse Gamma	1.00	∞	0.39	0.26	0.52
σ_{LOP}	law of one price gap	Inverse Gamma	1.00	∞	4.99	3.72	6.24
σ_{NW}	entrepreneurs' net worth	Inverse Gamma	1.00	∞	2.01	0.87	3.11
σ_Y	domestic productivity	Inverse Gamma	1.00	∞	3.81	2.15	5.43
σ_{MP}	monetary policy	Inverse Gamma	0.10	∞	0.08	0.06	0.09
σ_{y*}	foreign output	Inverse Gamma	0.50	∞	0.53	0.45	0.62
σ_{r*}	foreign inerest rate	Inverse Gamma	0.10	∞	0.05	0.05	0.06
$\sigma_{\pi*}$	foreign inflation rate	Inverse Gamma	0.20	∞	0.23	0.20	0.27

Source: Author.

Table D.2: Estimated parameters (SK model)

Parameter		Distribution	Prior Mean	Prior Std	Posterior Mean	95% HPDI	
Υ	habit persistence	Beta	0.60	0.05	0.57	0.49	0.66
Ψ	inverse elasticity of labour supply	Gamma	2.00	0.50	1.35	0.81	1.89
ψ^B	elasticity of debt-elastic risk premium	Gamma	0.05	0.02	0.05	0.02	0.08
η	home and foreign goods elasticity of substitution	Gamma	0.65	0.10	0.74	0.62	0.87
κ	price indexation	Beta	0.50	0.10	0.23	0.12	0.33
γ	preference bias to foreign goods	Beta	0.40	0.10	0.35	0.27	0.43
θ_H	home goods Calvo parameter	Beta	0.70	0.10	0.74	0.69	0.79
θ_F	foreign goods Calvo parameter	Beta	0.70	0.10	0.69	0.62	0.75
ψ^I	capital adjustment costs	Gamma	20.00	5.00	29.48	20.44	38.38
Γ	steady-state capital net worth ratio	Shifted Gamma	1.50	0.05	1.47	1.39	1.55
ς	entrepreneurs' bankruptcy rate	Beta	0.025	0.005	0.029	0.020	0.038
χ	financial accelerator	Gamma	0.050	0.010	0.043	0.030	0.056
Taylor rule							
ρ	interest rate smoothing	Beta	0.50	0.20	0.70	0.62	0.77
β_π	inflation weight	Shifted Gamma	1.50	0.20	1.83	1.49	2.16
Θ_y	output gap weight	Gamma	0.50	0.20	0.20	0.10	0.30
AR parameters							
ρ_{UIP}	debt-elastic risk premium	Beta	0.50	0.20	0.67	0.56	0.78
ρ_{LOP}	law of one price gap	Beta	0.50	0.20	0.72	0.60	0.85
ρ_{NW}	entrepreneurs' net worth	Beta	0.50	0.20	0.57	0.27	0.86
ρ_Y	domestic productivity	Beta	0.50	0.20	0.05	0.01	0.10
VAR parameters							
$\rho_{y^*y^*}$	interaction of y_t^* and y_{t-1}^*	Beta	0.80	0.10	0.89	0.82	0.97
$\rho_{\pi^*\pi^*}$	interaction of π_t^* and π_{t-1}^*	Beta	0.20	0.05	0.20	0.12	0.27
$\rho_{r^*r^*}$	interaction of r_t^* and r_{t-1}^*	Beta	0.60	0.20	0.56	0.42	0.70
$\rho_{y^*\pi^*}$	interaction of y_t^* and π_{t-1}^*	Normal	0.00	0.50	0.44	0.08	0.80
$\rho_{y^*r^*}$	interaction of y_t^* and r_{t-1}^*	Normal	0.00	0.50	-0.65	-1.18	-0.11
$\rho_{\pi^*y^*}$	interaction of π_t^* and y_{t-1}^*	Normal	0.00	0.50	0.15	0.07	0.22
$\rho_{\pi^*r^*}$	interaction of π_t^* and r_{t-1}^*	Normal	0.00	0.50	-0.66	-1.10	-0.23
$\rho_{r^*y^*}$	interaction of r_t^* and y_{t-1}^*	Normal	0.00	0.50	0.06	0.03	0.09
$\rho_{r^*\pi^*}$	interaction of r_t^* and π_{t-1}^*	Normal	0.00	0.50	0.04	-0.02	0.10
$\sigma_{\pi^*y^*}$	interaction of $\varepsilon_t^{\pi^*}$ and $\varepsilon_t^{y^*}$	Normal	0.50	0.25	0.15	0.05	0.24
$\sigma_{r^*y^*}$	interaction of $\varepsilon_t^{r^*}$ and $\varepsilon_t^{y^*}$	Normal	0.30	0.15	0.09	0.07	0.12
$\sigma_{r^*\pi^*}$	interaction of $\varepsilon_t^{r^*}$ and $\varepsilon_t^{\pi^*}$	Normal	0.00	0.50	-0.04	-0.09	0.00
Std of shocks							
σ_{UIP}	debt-elastic risk premium	Inverse Gamma	1.00	∞	0.65	0.48	0.82
σ_{LOP}	law of one price gap	Inverse Gamma	1.00	∞	4.94	3.73	6.09
σ_{NW}	entrepreneurs' net worth	Inverse Gamma	1.00	∞	5.75	2.22	9.22
σ_Y	domestic productivity	Inverse Gamma	1.00	∞	3.74	2.30	5.11
σ_{MP}	monetary policy	Inverse Gamma	0.10	∞	0.24	0.20	0.29
σ_{y*}	foreign output	Inverse Gamma	0.50	∞	0.53	0.45	0.61
σ_{r*}	foreign inerest rate	Inverse Gamma	0.10	∞	0.05	0.04	0.06
$\sigma_{\pi*}$	foreign inflation rate	Inverse Gamma	0.20	∞	0.23	0.20	0.27

Source: Author.

Table D.3: Estimated parameters (PL model)

Parameter		Distribution	Prior		Posterior		
			Mean	Std	Mean	95% HPDI	
Υ	habit persistence	Beta	0.60	0.05	0.58	0.50	0.67
Ψ	inverse elasticity of labour supply	Gamma	2.00	0.50	1.31	0.78	1.85
ψ^B	elasticity of debt-elastic risk premium	Gamma	0.05	0.02	0.04	0.02	0.06
η	home and foreign goods elasticity of substitution	Gamma	0.65	0.10	0.58	0.49	0.67
κ	price indexation	Beta	0.50	0.10	0.36	0.22	0.50
γ	preference bias to foreign goods	Beta	0.40	0.10	0.21	0.15	0.28
θ_H	home goods Calvo parameter	Beta	0.70	0.10	0.78	0.73	0.83
θ_F	foreign goods Calvo parameter	Beta	0.70	0.10	0.81	0.76	0.85
ψ^I	capital adjustment costs	Gamma	20.00	5.00	33.56	24.38	42.66
Γ	steady-state capital net worth ratio	Shifted Gamma	1.50	0.05	1.47	1.39	1.55
ς	entrepreneurs' bankruptcy rate	Beta	0.025	0.005	0.029	0.020	0.038
χ	financial accelerator	Gamma	0.050	0.010	0.042	0.029	0.055
Taylor rule							
ρ	interest rate smoothing	Beta	0.50	0.20	0.66	0.59	0.72
β_π	inflation weight	Shifted Gamma	1.50	0.20	1.99	1.60	2.36
Θ_y	output gap weight	Gamma	0.50	0.20	0.21	0.08	0.32
AR parameters							
ρ_{UIP}	debt-elastic risk premium	Beta	0.50	0.20	0.80	0.71	0.90
ρ_{LOP}	law of one price gap	Beta	0.50	0.20	0.86	0.82	0.91
ρ_{NW}	entrepreneurs' net worth	Beta	0.50	0.20	0.55	0.28	0.81
ρ_Y	domestic productivity	Beta	0.50	0.20	0.13	0.02	0.23
VAR parameters							
$\rho_{y^*y^*}$	interaction of y_t^* and y_{t-1}^*	Beta	0.80	0.10	0.89	0.82	0.97
$\rho_{\pi^*\pi^*}$	interaction of π_t^* and π_{t-1}^*	Beta	0.20	0.05	0.20	0.12	0.27
$\rho_{r^*r^*}$	interaction of r_t^* and r_{t-1}^*	Beta	0.60	0.20	0.56	0.41	0.70
$\rho_{y^*\pi^*}$	interaction of y_t^* and π_{t-1}^*	Normal	0.00	0.50	0.47	0.12	0.82
$\rho_{y^*r^*}$	interaction of y_t^* and r_{t-1}^*	Normal	0.00	0.50	-0.50	-1.09	0.06
$\rho_{\pi^*y^*}$	interaction of π_t^* and y_{t-1}^*	Normal	0.00	0.50	0.14	0.07	0.22
$\rho_{\pi^*r^*}$	interaction of π_t^* and r_{t-1}^*	Normal	0.00	0.50	-0.57	-1.02	-0.12
$\rho_{r^*y^*}$	interaction of r_t^* and y_{t-1}^*	Normal	0.00	0.50	0.06	0.04	0.09
$\rho_{r^*\pi^*}$	interaction of r_t^* and π_{t-1}^*	Normal	0.00	0.50	0.04	-0.02	0.11
$\sigma_{\pi^*y^*}$	interaction of $\varepsilon_t^{\pi^*}$ and $\varepsilon_t^{y^*}$	Normal	0.50	0.25	0.15	0.05	0.25
$\sigma_{r^*y^*}$	interaction of $\varepsilon_t^{r^*}$ and $\varepsilon_t^{y^*}$	Normal	0.30	0.15	0.09	0.07	0.12
$\sigma_{r^*\pi^*}$	interaction of $\varepsilon_t^{r^*}$ and $\varepsilon_t^{\pi^*}$	Normal	0.00	0.50	-0.05	-0.10	0.00
Std of shocks							
σ_{UIP}	debt-elastic risk premium	Inverse Gamma	1.00	∞	0.46	0.29	0.62
σ_{LOP}	law of one price gap	Inverse Gamma	1.00	∞	6.92	5.57	8.23
σ_{NW}	entrepreneurs' net worth	Inverse Gamma	1.00	∞	2.40	1.07	3.70
σ_Y	domestic productivity	Inverse Gamma	1.00	∞	1.64	1.01	2.28
σ_{MP}	monetary policy	Inverse Gamma	0.10	∞	0.21	0.17	0.25
σ_{y*}	foreign output	Inverse Gamma	0.50	∞	0.54	0.45	0.62
σ_{r*}	foreign inerest rate	Inverse Gamma	0.10	∞	0.05	0.04	0.06
$\sigma_{\pi*}$	foreign inflation rate	Inverse Gamma	0.20	∞	0.23	0.20	0.27

Source: Author.

Table D.4: Estimated parameters (HU model)

Parameter		Distribution	Prior Mean	Prior Std	Posterior Mean	95% HPDI	
Υ	habit persistence	Beta	0.60	0.05	0.59	0.51	0.68
Ψ	inverse elasticity of labour supply	Gamma	2.00	0.50	1.35	0.78	1.90
ψ^B	elasticity of debt-elastic risk premium	Gamma	0.05	0.02	0.05	0.02	0.08
η	home and foreign goods elasticity of substitution	Gamma	0.65	0.10	0.59	0.50	0.69
κ	price indexation	Beta	0.50	0.10	0.37	0.22	0.53
γ	preference bias to foreign goods	Beta	0.40	0.10	0.24	0.15	0.32
θ_H	home goods Calvo parameter	Beta	0.70	0.10	0.69	0.57	0.83
θ_F	foreign goods Calvo parameter	Beta	0.70	0.10	0.66	0.54	0.79
ψ^I	capital adjustment costs	Gamma	20.00	5.00	36.08	25.82	46.16
Γ	steady-state capital net worth ratio	Shifted Gamma	1.50	0.05	1.47	1.39	1.54
ς	entrepreneurs' bankruptcy rate	Beta	0.025	0.005	0.029	0.020	0.038
χ	financial accelerator	Gamma	0.050	0.010	0.040	0.028	0.053
Taylor rule							
ρ	interest rate smoothing	Beta	0.50	0.20	0.68	0.58	0.78
β_π	inflation weight	Shifted Gamma	1.50	0.20	2.00	1.55	2.41
Θ_y	output gap weight	Gamma	0.50	0.20	0.23	0.10	0.35
AR parameters							
ρ_{UIP}	debt-elastic risk premium	Beta	0.50	0.20	0.77	0.67	0.88
ρ_{LOP}	law of one price gap	Beta	0.50	0.20	0.83	0.76	0.90
ρ_{NW}	entrepreneurs' net worth	Beta	0.50	0.20	0.52	0.23	0.81
ρ_Y	domestic productivity	Beta	0.50	0.20	0.65	0.26	0.95
VAR parameters							
$\rho_{y^*y^*}$	interaction of y_t^* and y_{t-1}^*	Beta	0.80	0.10	0.89	0.81	0.97
$\rho_{\pi^*\pi^*}$	interaction of π_t^* and π_{t-1}^*	Beta	0.20	0.05	0.20	0.12	0.27
$\rho_{r^*r^*}$	interaction of r_t^* and r_{t-1}^*	Beta	0.60	0.20	0.54	0.40	0.68
$\rho_{y^*\pi^*}$	interaction of y_t^* and π_{t-1}^*	Normal	0.00	0.50	0.44	0.08	0.80
$\rho_{y^*r^*}$	interaction of y_t^* and r_{t-1}^*	Normal	0.00	0.50	-0.60	-1.15	-0.07
$\rho_{\pi^*y^*}$	interaction of π_t^* and y_{t-1}^*	Normal	0.00	0.50	0.13	0.06	0.21
$\rho_{\pi^*r^*}$	interaction of π_t^* and r_{t-1}^*	Normal	0.00	0.50	-0.57	-1.01	-0.13
$\rho_{r^*y^*}$	interaction of r_t^* and y_{t-1}^*	Normal	0.00	0.50	0.06	0.04	0.09
$\rho_{r^*\pi^*}$	interaction of r_t^* and π_{t-1}^*	Normal	0.00	0.50	0.04	-0.02	0.10
$\sigma_{\pi^*y^*}$	interaction of $\varepsilon_t^{\pi^*}$ and $\varepsilon_t^{y^*}$	Normal	0.50	0.25	0.15	0.06	0.25
$\sigma_{r^*y^*}$	interaction of $\varepsilon_t^{r^*}$ and $\varepsilon_t^{y^*}$	Normal	0.30	0.15	0.09	0.07	0.12
$\sigma_{r^*\pi^*}$	interaction of $\varepsilon_t^{r^*}$ and $\varepsilon_t^{\pi^*}$	Normal	0.00	0.50	-0.05	-0.10	0.00
Std of shocks							
σ_{UIP}	debt-elastic risk premium	Inverse Gamma	1.00	∞	0.49	0.30	0.67
σ_{LOP}	law of one price gap	Inverse Gamma	1.00	∞	6.28	4.86	7.68
σ_{NW}	entrepreneurs' net worth	Inverse Gamma	1.00	∞	2.98	1.21	4.69
σ_Y	domestic productivity	Inverse Gamma	1.00	∞	1.52	0.58	2.91
σ_{MP}	monetary policy	Inverse Gamma	0.10	∞	0.30	0.24	0.35
σ_{y*}	foreign output	Inverse Gamma	0.50	∞	0.53	0.45	0.61
σ_{r*}	foreign inerest rate	Inverse Gamma	0.10	∞	0.05	0.04	0.06
$\sigma_{\pi*}$	foreign inflation rate	Inverse Gamma	0.20	∞	0.23	0.20	0.27

Source: Author.

Table D.5: Estimated parameters (EA model)

Parameter		Distribution	Prior		Posterior		
			Mean	Std	Mean	95% HPDI	
Υ	habit persistence	Beta	0.60	0.05	0.66	0.56	0.77
Ψ	inverse elasticity of labour supply	Gamma	2.00	0.50	1.18	0.66	1.67
ψ^B	elasticity of debt-elastic risk premium	Gamma	0.05	0.02	0.02	0.01	0.03
η	home and foreign goods elasticity of substitution	Gamma	0.65	0.10	0.46	0.43	0.48
κ	price indexation	Beta	0.50	0.10	0.21	0.11	0.30
γ	preference bias to foreign goods	Beta	0.40	0.10	0.21	0.16	0.25
θ_H	home goods Calvo parameter	Beta	0.70	0.10	0.81	0.77	0.86
θ_F	foreign goods Calvo parameter	Beta	0.70	0.10	0.82	0.77	0.86
ψ^I	capital adjustment costs	Gamma	20.00	5.00	27.31	18.99	35.32
Γ	steady-state capital net worth ratio	Shifted Gamma	1.50	0.05	1.47	1.39	1.55
ς	entrepreneurs' bankruptcy rate	Beta	0.025	0.005	0.027	0.019	0.035
χ	financial accelerator	Gamma	0.050	0.010	0.040	0.028	0.052
Taylor rule							
ρ	interest rate smoothing	Beta	0.50	0.20	0.72	0.65	0.79
β_π	inflation weight	Shifted Gamma	1.50	0.20	1.67	1.38	1.95
Θ_y	output gap weight	Gamma	0.50	0.20	0.18	0.08	0.27
AR parameters							
ρ_{UIP}	debt-elastic risk premium	Beta	0.50	0.20	0.77	0.70	0.83
ρ_{LOP}	law of one price gap	Beta	0.50	0.20	0.82	0.78	0.86
ρ_{NW}	entrepreneurs' net worth	Beta	0.50	0.20	0.42	0.17	0.67
ρ_Y	domestic productivity	Beta	0.50	0.20	0.07	0.01	0.13
VAR parameters							
$\rho_{y^*y^*}$	interaction of y_t^* and y_{t-1}^*	Beta	0.80	0.10	0.79	0.70	0.88
$\rho_{\pi^*\pi^*}$	interaction of π_t^* and π_{t-1}^*	Beta	0.20	0.05	0.19	0.11	0.26
$\rho_{r^*r^*}$	interaction of r_t^* and r_{t-1}^*	Beta	0.60	0.20	0.86	0.77	0.96
$\rho_{y^*\pi^*}$	interaction of y_t^* and π_{t-1}^*	Normal	0.00	0.50	0.11	-0.08	0.30
$\rho_{y^*r^*}$	interaction of y_t^* and r_{t-1}^*	Normal	0.00	0.50	0.58	0.18	0.97
$\rho_{\pi^*y^*}$	interaction of π_t^* and y_{t-1}^*	Normal	0.00	0.50	-0.02	-0.12	0.08
$\rho_{\pi^*r^*}$	interaction of π_t^* and r_{t-1}^*	Normal	0.00	0.50	0.32	-0.09	0.73
$\rho_{r^*y^*}$	interaction of r_t^* and y_{t-1}^*	Normal	0.00	0.50	0.02	-0.01	0.04
$\rho_{r^*\pi^*}$	interaction of r_t^* and π_{t-1}^*	Normal	0.00	0.50	-0.02	-0.06	0.02
$\sigma_{\pi^*y^*}$	interaction of $\varepsilon_t^{\pi^*}$ and $\varepsilon_t^{y^*}$	Normal	0.50	0.25	0.35	0.19	0.52
$\sigma_{r^*y^*}$	interaction of $\varepsilon_t^{r^*}$ and $\varepsilon_t^{y^*}$	Normal	0.30	0.15	0.09	0.05	0.12
$\sigma_{r^*\pi^*}$	interaction of $\varepsilon_t^{r^*}$ and $\varepsilon_t^{\pi^*}$	Normal	0.00	0.50	0.02	-0.02	0.06
Std of shocks							
σ_{UIP}	debt-elastic risk premium	Inverse Gamma	1.00	∞	0.41	0.27	0.54
σ_{LOP}	law of one price gap	Inverse Gamma	1.00	∞	7.10	5.81	8.39
σ_{NW}	entrepreneurs' net worth	Inverse Gamma	1.00	∞	1.66	0.82	2.47
σ_Y	domestic productivity	Inverse Gamma	1.00	∞	1.75	0.96	2.50
σ_{MP}	monetary policy	Inverse Gamma	0.10	∞	0.07	0.06	0.08
σ_{y*}	foreign output	Inverse Gamma	0.50	∞	0.57	0.49	0.65
σ_{r*}	foreign inerest rate	Inverse Gamma	0.10	∞	0.09	0.07	0.10
$\sigma_{\pi*}$	foreign inflation rate	Inverse Gamma	0.20	∞	0.50	0.43	0.57

Source: Author.