STRUCTURAL CHANGES IN THE CZECH ECONOMY: A DSGE MODEL APPROACH

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Abstract

This article identifies structural changes in the Czech economy in the period from 1996 to 2012 using a DSGE model estimated using Bayesian methods. A structural change is understood as a statistically significant change in model parameter(s).

Prior to the first quarter of 1999, there was a structural change that can be primarily attributed to shocks impacting only the domestic economy, and to the domestic monetary authority's increased preferences towards inflation and exchange rate growth. The elasticity of substitution between domestic and imported consumption goods also increased sharply in this period. As far as the recent economic recession is concerned, it was caused by a much more persistent world-wide technology shock. Habit formation dropped abruptly during the crisis as households tended not to smooth their consumption much anymore.

Recursive impulse response analysis carried out on the model suggests that the propagation mechanisms in the model economy changed, implying that the identified structural changes were accompanied by a change in behaviour of the model economy.

Keywords: DSGE model, Bayesian estimation, structural change, rolling estimation, recursive impulse response

JEL Classification: C11, D58, E32

1. Introduction

More than 50 years ago, econometricians' interest in structural breaks resulted in Chow (1960) proposing a simple time series statistical test for them. Recently, with the growing use of Dynamic Stochastic General Equilibrium (henceforth DSGE) models in economic analysis, a number of authors have addressed the issue of structural changes in the context of DSGE models. Structural changes should be of special interest for researchers who use DSGE models for policy analysis or predictions, since ignoring structural changes may lead to inaccurate forecasts and misleading policy recommendations. Unfortunately, following *e.g.* Chow's (1960) methodology in these cases is not possible because, as Lubik and Surico (2010) point out, formal break tests have not yet been fully established for DSGE models estimated using Bayesian methods.

The literature that examines structural changes in the context of the recent recession in various countries is significant (see *e.g.* Jerger and Röhe, 2012; and Lee, 2012). For the Czech economy, the study by Tonner *et al.* (2011) has been the only study published

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so far which addresses structural changes in a DSGE model setting.[1, 2] To the best of my knowledge, this is the first study on the Czech economy that reports the *statistical significance of parameter changes* in a DSGE model estimated using Bayesian techniques.

This paper attempts to complement Tonner *et al*. (2011) and to bridge a gap in the existing literature with the study that focuses on identifying structural changes within a DSGE model estimated using Bayesian techniques on Czech data. The existing literature on identifying structural changes within DSGE models uses *ad-hoc* approaches which limit comparability, whereas this paper offers a comprehensive methodology and applies it to a suitable small open economy model of the Czech economy.

As for the definition of the fundamental term "structural change", this is not unified in the relevant literature.[3] To make the results clear, this paper defines a "structural change" as a statistically significant change in one or more model parameters.

2. Structural Changes in DSGE Models

Two different approaches are used for the estimation of structural changes in DSGE literature: either a split-sample approach (or its variants), or a full-fledged parameter drift.

Canova (2006 and 2009) uses a small-scale New Keynesian DSGE model for the so-called "rolling analysis" or "recursive analysis". The analysis builds on a Bayesian estimation, which has been carried out many times for different time-frames. Canova finds that private sector parameters change considerably, whereas changes in policy parameters are insignificant.

Fernández-Villaverde and Rubio-Ramírez (2008) estimate full-fledged drifting parameters, albeit only a couple at a time. This parameter drift is rationally expected by economic agents. A drawback of the methodology is that it does not explain the reason for the parameter change, and this drawback is further deepened by the computational cost of the procedure, which does not allow a greater number of drifting parameters to be estimated simultaneously. The authors find great variation in the estimates of several parameters, some of which (*e.g.* Calvo parameters modelling nominal rigidities) they consider alarming.

In a comment to the aforementioned article by Fernández-Villaverde and Rubio-Ramírez, Schorfheide (2008) shows through a subsample analysis that statistically different parameter estimates produce statistically almost the same impulse response functions, which raises the question of how to interpret changes in structural parameters. In another comment, Cogley (2008) stresses that the one-at-a-time approach used in the paper to model the parameter drift is inappropriate. More specifically, policy and Calvo parameters should drift together.

2.1 Parameter estimates and their statistical significance

Once the parameters have been estimated, it is important to decide which parameter changes are big enough to be addressed as structural changes. The approaches used in the existing literature vary.

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1   I refer here to journal articles; it should be noted that Tonner's dissertation also relates to the topic, as do two of the author's conference contributions: Čapek (2011) is a preliminary, 6-page-long version of this paper, while Čapek (2012) provides a sensitivity analysis with nonlinear filtration.

2   In the meantime, two author's journal articles using the methodology proposed in this paper were published: Čapek (2014) and Čapek (2015) focus on real-time data issues of searching for structural changes.

3   For example, Boivin and Giannoni (2002, pp. 4–8) understand structural change in the economy in the same way as structural change in parameters. Rubio-Ramírez *et al*. (2005, p. 11) see structural change as a change in the volatility of shocks and/or a shift in parameter values.

Some authors completely disregard the uncertainty connected to the estimate, and concentrate on point estimates (Benati, 2008b; Tonner *et al.,* 2011).

Another branch of the literature investigates whether the probability bands of different estimates overlap or not (Schorfheide, 2008; Canova and Gambetti, 2009). An attempt to show whether a point estimate from one estimation fits into the probability interval of another estimate (Pivetta and Reis, 2007) is a variation to this approach.

After determining which of these approaches to follow, the investigator must then decide the significance threshold at which the result can be called a structural change. The practice varies from use of 10% significance level (Benati, 2008a) up to the 50% significance level (Cogley and Sargent, 2002).

3. Methodology

This paper follows a split-sample approach similar to Canova (2009) and extends it. The extension serves two purposes: firstly, it is used as a sensitivity analysis to find out whether a different specification still identifies a structural change; secondly, it allows future comparability of the results, as it offers calculation results consistent with virtually all approaches in the split-sample literature (see Section 2.1).

3.1 Recursive, "first observation" and rolling analyses

Essentially, there are three possible approaches to systematic split-sample estimation: (i) recursive, (ii) "first observation", and (iii) rolling analysis. All of these approaches comprise many successive estimations, in which given observations at the beginning and/or end of the time sample are omitted in the estimation.

The sensitivity of the estimate to the choice of the last observation is known in the literature as recursive analysis. The first observation (arbitrarily chosen somewhere at the beginning of the time series) is fixed, while the last observation shifts by a quarter each time a new estimation is carried out. The series of such estimates may be intuitively perceived as an exploration of the information in the newly-added data.

The so-called "first observation" analysis is another split-sample estimation approach, in which the last observation is fixed (the latest available observation), and the first observation varies by a quarter each time a new estimation is carried out. These estimates reflect the sensitivity of the estimate to the choice of the first observation.

Rolling analysis addresses the drawback of the two previous analyses, which is changing size of the time frame – this is overcome by estimating in a moving window, which ensures that the size of the time frame remains unchanged. A rolling analysis carried out with a suitable size of time frame serves as an excellent sensitivity analysis tool and is not presented here.[4]

In order to concur with the various approaches mentioned in the literature review, this paper calculates results for all of these possibilities. However, since the group of indicators based on the posterior distribution and the group of indicators using point estimates give similar results in most of the cases, the full set of results is not presented here.

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4   The role of rolling analysis in identification of structural changes can be illustrated on parameter ρ_r. Although recursive analysis on a full sample indicates that this parameter rises throughout the whole time period studied, a rolling analysis in conjunction with "first observation" analysis shows that the gradual rise in the recursive estimate is illusory. The new information added recursively in the recursive estimate just dilutes the strong information in the first observations.

This paper therefore shows significance values for only two indicators, the first being the union of the two respective normalized posterior densities as a measure based on the whole posterior distribution. The second set of significance values is based on the lowest significance level at which the mode is outside the Highest Posterior Density bands. The second indicator is representative of a point estimate approach.

4. Model

This article uses a New Keynesian (NK) Dynamic Stochastic General Equilibrium (DSGE) model. The model is derived from the microeconomic behaviour of particular economic agents. These include domestic and foreign households, domestic and foreign producers, domestic importers and domestic and foreign monetary authority.

I have adjusted the original two-country model described by Lubik and Schorfheide (2006) to fit for a small open economy (SOE) setting. The adjusted model consists of a small open economy which is influenced by a big closed economy (and not *vice versa*). The small open economy is the home economy; the big closed economy is the foreign economy.

Log-linearized variables are in log-deviations from steady state, where $x_t = log X_t - log X$, and where variable (X_t) can be separated into two parts: a steady-state value denoted by the capital letter without time subscript (X) and a gap value denoted by the lowercase letter with time subscript (x_t).

When applicable, variables with H subscript (*e.g.* $X_{H,t}$) denote goods produced and activities associated with the Home economy and variables with F subscript (*e.g.* $X_{F,t}$) denote goods produced and activities associated with the Foreign economy. The location of the economic activities is denoted with a star superscript (*e.g.* X_t^*) for the foreign economy and is left without extra notation for the home economy.

The log-linearized model has the following form. Starting with households, the system contains equations for the evolution of marginal utility of income (1), the law of motion of habit stock (2), the Euler Equation (3), and the definition of inflation from domestic and imported inflation (4):

$$-\lambda_t = \frac{\tau}{1-h\beta}c_t - \frac{h\beta}{1-h\beta}E_t(\tau c_{t+1} + z_{t+1}) \tag{1}$$

$$c_t = \frac{1}{1-h}(c_t - hc_{t-1} + hz_t) \tag{2}$$

$$-\lambda_t = -E_t\lambda_{t+1} - (r_t - E_t\pi_{t+1}) + E_t z_{t+1} \tag{3}$$

$$\pi_t = (1-\alpha)\pi_{H,t} + \alpha\pi_{F,t}, \tag{4}$$

where λ_t is marginal utility of real income, c_t is household's consumption, E_t is an expectations operator, z_t is the growth coefficient of a world-wide technology shock (as AR1 shock), r_t is the nominal interest rate and π_t is inflation. For the interpretation of the parameters, see Table 1 below.

The behaviour of the producers yields the New-Keynesian Phillips Curve (5) with marginal cost evolution described by (6)

$$\pi_{H,t} = \frac{1-\theta_H}{\theta_H}(1-\beta\theta_H)mc_{H,t} + \beta E_t\pi_{H,t+1} \tag{5}$$

$$mc_{H,t} = -\alpha q_t - \lambda_t - a_t \tag{6}$$

where $mc_{H,t}$ are domestic marginal costs, q_t are the terms of trade and a_t is AR1 country-specific technology shock.

Importers' optimization is analogous to that of the producers and yields an importers' Phillips curve (7)

$$\pi_{F,t} = \frac{1-\theta_F}{\theta_F}(1-\beta\theta_F)\psi_{F,t} + \beta E_t \pi_{F,t+1} \tag{7}$$

where $\psi_{F,t}$ is the law of one price (LOP) gap.

The definition of the depreciation rate of the nominal exchange rate is (8), differenced definition of terms of trade is (9) and the combined definition of the real exchange rate and LOP gap is (10).

$$\Delta e_t = \Delta s_t + \pi_t - \pi_t^*, \tag{8}$$

$$q_t = q_{t-1} + \pi_{H,t} - \pi_{F,t} \tag{9}$$

$$s_t = \psi_{F,t} - (1-\alpha)q_t \tag{10}$$

where e_t is the nominal exchange rate in direct quotation and s_t is the real exchange rate.

The model is supplemented with equilibria equations that include equations for international risk-sharing (11), uncovered interest parity (UIP) conditions (12) and market clearing (13).

$$\lambda_t = \lambda_t^* - s_t. \tag{11}$$

$$r_t - r_t^* = E_t \Delta e_{t+1} \tag{12}$$

$$y_{H,t} = (1-\alpha)c_t + \alpha c_t^* + \alpha\eta(s_t - q_t) + g_{H,t} \tag{13}$$

where $g_{H,t}$ are government expenditures modelled as AR1 shock.

The foreign economy is modelled structurally so that there are foreign households and producers that also show optimizing behaviour. However, since the foreign economy is big and closed, its agents are not influenced in their optimization behaviour by the activities of the home economy.

The following equations are introduced in analogy to the home case: the foreign households' optimizing behaviour (14) and (15), the foreign producers' Phillips curve (16) and a collapsed version of market clearing (17).

$$-\lambda_t^* = \frac{\tau}{1-h\beta}c_t^* - \frac{h\beta}{1-h\beta}E_t(\tau c_{t+1}^* + z_{t+1}) \tag{14}$$

$$c_t^* = \frac{1}{1-h}(c_t^* - hc_{t-1}^* + hz_t) \tag{15}$$

$$\pi_t^* = \frac{1-\theta^*}{\theta^*}(1-\beta\theta^*)(-\lambda_t^* - a_t^*) + \beta E_t \pi_{t+1}^* \tag{16}$$

$$y_t^* = c_t^* + g_t^* \tag{17}$$

The model is closed by specifying monetary policy with a Taylor-type rule. This formulation of monetary policy assumes that central banks respond to deviations in inflation from steady state, in output growth rate from steady state growth rate, and possibly to deviations in nominal exchange rate depreciation from steady state. Home and foreign monetary rules are therefore

$$r_t = \rho_r r_{t-1} + (1 - \rho_r)[\psi_1 \pi_t + \psi_2 (\Delta y_{H,t} + z_t) + \psi_3 \Delta e_t] + \varepsilon_{r,t} \qquad (18)$$

$$r_t^* = \rho_r^* r_{t-1}^* + (1 - \rho_r^*)[\psi_1^* \pi_t^* + \psi_2^* (\Delta y_t^* + z_t)] + \varepsilon_{r,t}^*, \qquad (19)$$

where ε s are IID innovations.

Table 1 | Summary of Model Parameters

Par.	Description
β	future utility discount factor
θ_H	fraction of domestic producers who do not change prices
θ_F	fraction of importers who do not change prices
θ_F^*	fraction of foreign producers who do not change prices
τ	coefficient of relative risk aversion
h	habit (persistence) in consumption
α	part of domestic consumption that comes from goods produced in foreign economy (import share)
η	intratemporal elasticity of substitution between domestic and imported consumption goods
ψ_1	weight on inflation in domestic monetary rule
ψ_2	weight on output growth in domestic monetary rule
ψ_3	weight on nominal depreciation in domestic monetary rule
ψ_1^*	weight on inflation in foreign monetary rule
ψ_2^*	weight on output growth in foreign monetary rule
ρ_a	AR1 persistence in domestic supply shock
ρ_r	AR1 persistence in domestic monetary rule
ρ_g	AR1 persistence in domestic demand shock
ρ_a^*	AR1 persistence in foreign supply shock
ρ_r^*	AR1 persistence in foreign monetary rule
ρ_g	AR1 persistence in foreign demand shock
ρ_z	AR1 persistence in the growth rate of world-wide technology shock

Source: Lubik and Schorfheide (2006)

5. Taking the Model to the Data

5.1 Data

The observable variables were chosen in accordance with Lubik and Schorfheide (2006), who use quarterly data for seven observable variables – output growth, CPI inflation and 3-month nominal interest rate – for both the domestic and foreign economies – and the growth rate of the bilateral nominal exchange rate.

The data sample starts in the first quarter of 1996 and ends in the fourth quarter of 2012 with 68 observations in total. Note that one observation is lost due to differentiation. All the data was extracted from the Eurostat database.

The model has zero steady-states and the data was detrended prior to estimation. With the exception of the interest rates, all series are demeaned. Both series of interest rates apparently have a non-constant trend. The linear time trend is sufficient for detrending the foreign interest rate, but the domestic interest rate exhibits greater curvature, and was detrended using the Hodrick-Prescott filter.[5]

5.2 Identification

The log-linearized DSGE model was estimated using Bayesian methods. A numerical-optimization procedure was used to maximize the posterior. A million draws from posterior density were generated with a random-walk Metropolis-Hastings algorithm, after which the convergence was checked according to the convergence diagnostics described by Brooks and Gelman (1998). If the chain did not converge, 1,000,000 more samples were added, and the convergence was rechecked until convergence was reached. 90% of the original sample was then discarded, and the rest was used for posterior analysis.

The estimation was carried out using Dynare software[6]. A Monte-Carlo based optimization routine was used for computing the mode, so that the different estimates all reached a suitable acceptation rate.

6. Identification of Structural Changes

This section identifies structural changes in a DSGE model estimated using Bayesian techniques. The following strategy is employed: Subsection 6.1 uses "first observation" analysis to identify structural changes at the beginning of the time sample. Subsection 6.2 uses recursive analysis (with starting date 1999q1) to identify structural changes towards the end of the time sample.

Rolling analysis was used to check the middle of the time sample for structural changes, and none were identified. It was also used to select 1999q1 as a suitable starting date for the recursive analysis.

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5   For an analysis of the economic balance of the Czech Republic during the recent economic crisis, see Bolotov et al. (2013). For a broader perspective on the macroeconomic growth and stability of the Czech economy, see Spěváček (2013).

6   Version 4.3.2.

6.1 Structural changes identified by "first observation" analysis

Table 2 | Significance Values, "First Observation" Estimates

parameter		area	sig_mode	change in post. mean (with timing)
θ_H	Calvo – domestic	0.65	0.36	
θ_F	Calvo – foreign	0.45	0.12	
θ_F^*	Calvo – importers	0.78	0.59	
τ	relative risk aversion	0.77	0.64	
h	habit	0.53	0.17	
α	import share	0.64	0.35	
η	elast. subst. domest./imp. cons.	0.07*	0.01***	from 0.2 (1998q1) to 0.7 (2004q1)
ψ_1	dom. Taylor – inflation	0.16	0.01***	from 1 (1997q2) to 1.4 (1998q3)
ψ_2	dom. Taylor – output growth	0.47	0.16	
ψ_3	dom. Taylor – nom. exch. rate growth	0.44	0.10*	from 0.09 (1998q3) to 0.13 (1999q2)
ψ_1^*	for. Taylor – inflation	0.78	0.49	
ψ_1^*	for. Taylor – output growth	0.67	0.50	
ρ_a	AR1 – dom. supply shock	0.12	0.01***	from 0.9 (1997q2) to 0.7 (1998q4)
ρ_r	dom. Taylor – backwrd.-look.	0.00***	0.01***	from 0.65 (1997q1) to 0.85 (1999q1)
ρ_g	AR1 – dom. demand shock	0.11	0.01***	from 0.95 (2000q4) to 0.85 (2004q3)
ρ_a^*	AR1 – for. supply shock	0.54	0.20	
ρ_r	for. Taylor – backwrd.-look.	0.71	0.45	
ρ_g	AR1 – for. demand shock	0.76	0.54	
ρ_z	AR1 – gr.rate of wrld.-wide tech. shock	0.65	0.23	

Notes: *area* denotes the overlap of the normalized posterior densities (1=identical densities, 0=densities do not have any common point), *sig_mode* denotes the lowest level of significance at which posterior mode lies outside the Highest Posterior Density interval bands for the most different estimates. Values lower than or equal to 0.1 are denoted with a star, those lower than or equal to 0.05 with two stars, and those lower than or equal to 0.01 with three stars. Due to the computational procedure used, the values in column *sig_mode* have been rounded up. Statistically significant results discussed in the text are highlighted.

Source: Own calculations

Table 2 presents the results of structural change identification using "first observation" analysis. In the following text, the focus will be only on structural changes identified as significant at the 10% level.

The elasticity of substitution between domestic and imported consumption goods, η, more than triples in a gradual fashion between 1998q1 and 2004q1. This indicates that domestic consumers gradually encountered less difficulty when substituting domestic for imported consumption goods. Since this period may be seen as a period of economic recovery in the aftermath of the monetary crisis, such a tendency seems plausible. The rise in η may also be part of a mutual effect with import share, α, which also increases (though insignificantly) in this period.[7]

The weight on inflation in domestic monetary rule ψ_1 increases from a little over 1 in 1997q2 to 1.4 in 1998q3. This change clearly corresponds to a monetary crisis and a switch to an inflation targeting regime by the Czech National Bank (CNB). Since 1998, the CNB has explicitly targeted inflation, hence the rise in the Bank's preference towards inflation in monetary rule.

The evolution of the persistence of domestic supply shock, ρ_α, is curious since it tends to values around 0.8 throughout the whole period under observation, the exception being the period between 1997q2 and 1998q4. The persistence jumps up from 0.8 to 0.9 in 1997q2, gradually declines to 0.7 in 1998q4, and then converges back to around 0.8. Clearly, the transmission mechanism of this shock changes during and in the aftermath of the monetary crisis. An inspection of the workings of shocks within the model is beyond the scope of this paper; however, some aspects of the mutual effects are addressed in Section 8 together with the impulse response analysis.

The structural change in the backward-looking parameter in the domestic monetary rule, ρ_r, is the most significant of the structural changes identified. The parameter ρ_r increases from 0.65 in 1997q1 to 0.85 in 1999q1. Incorporation of the inflation targeting regime and a decline in interest rate volatility both lead to a greater part of the interest rate value depending on its previous value. In other words, the interest rate value depends less on the monetary authority's quarter-to-quarter decisions. This interpretation is in line with the stabilization of interest rates, which occurred soon after the introduction of the inflation targeting regime.

A characteristics common to all the structural breaks discussed is that none of the parameters in question pertains to the foreign economy. In other words, the results in Table 2 indicate that the Czech Republic experienced structural changes in the mid-1990s, but the euro area did not.

6.2 Structural changes identified by recursive analysis

Table 3 presents the significance values based on recursive estimates using data from 1999.

The first structural change identified in Table 3 relates to a parameter describing habit in consumption, h. The evolution of this parameter in time and the two respective posterior densities used for identification of the structural break are depicted in Figure 1. The habit factor is constant at 0.8 until the crisis hits the economy in 2008q4, dropping to below 0.6 until the following quarter. This demonstrates that the economic crisis was extraordinary in this period, because the value of the shock itself is not sufficient to explain the consequences – the preference parameter of domestic households that describes their consumption smoothing also goes down.

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7   See Equation 13

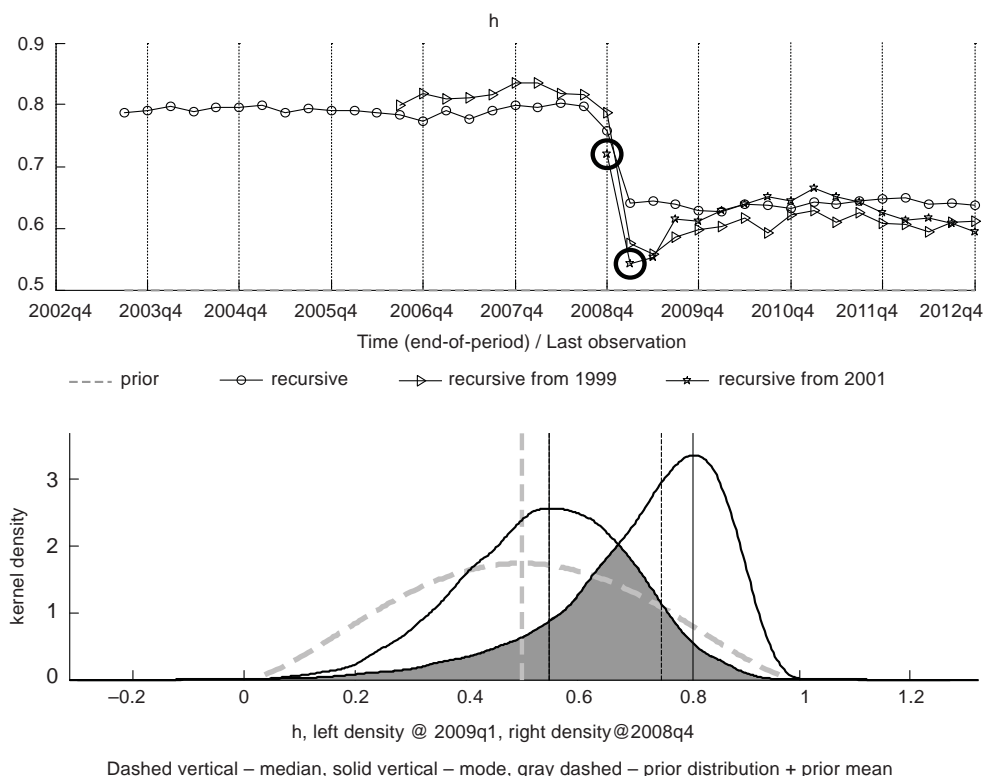**Table 3 | Significance Values, Recursive Estimates from Year 1999**

parameter		area	sig_mode	change in post. mean (with timing)
θ_H	Calvo – domestic	0.79	0.46	
θ_F	Calvo – foreign	0.64	0.34	
θ_F^*	Calvo – importers	0.55	0.23	
τ	relative risk aversion	0.55	0.21	
h	habit	0.21	0.02**	from 0.8 (2008q4) to 0.6 (2009q1)
α	import share	0.66	0.36	
η	elast. subst. domest./imp. cons.	0.41	0.07*	from 0.6 (2008q2) to 0.4 (2009q2)
ψ_1	dom. Taylor – inflation	0.57	0.20	
ψ_2	dom. Taylor – output growth	0.26	0.01***	from 0.8 (2008q2) to 0.5 (2008q4)
ψ_3	dom. Taylor – nom. exch. rate growth	0.69	0.39	
ψ_1^*	for. Taylor – inflation	0.68	0.40	
ψ_2^*	for. Taylor – output growth	0.60	0.23	
ρ_a	AR1 – dom. supply shock	0.59	0.27	
ρ_r	dom. Taylor – backwrd.-look.	0.63	0.36	
ρ_g	AR1 – dom. demand shock	0.62	0.53	
ρ_a^*	AR1 – for. supply shock	0.42	0.07*	from 0.7 (2006q4) to 0.8 (2007q4)
ρ_r^*	for. Taylor – backwrd.-look.	0.36	0.05**	from 0.8 (2008q2) to 0.85 (2008q4)
ρ_g	AR1 – for. demand shock	0.90	0.73	
ρ_z	AR1 – gr.rate of wrld.-wide tech. shock	0.27	0.02**	from 0.35 (2008q4) to 0.55 (2009q1)

Note: For detailed explanatory notes, see Table 2.
Source: Own calculation

Parallel to h is the interpretation for persistence in the growth rate of world-wide technology shock ρ_z. At the same time as habit h drops, ρ_z jumps up. The fact that this shock almost doubled in persistence during the crisis can be explained by the nature of the crisis; the crisis was global, and is therefore captured by a world-wide shock. Also, it was severe and long, and this resulted in the persistence of the shock increasing. In the post-crisis evolution of both parameters h and ρ_z, we observe that neither returned to their pre-crisis values. The change in the transmission mechanism of world-wide shocks is therefore long-term. Also, it can be argued that the model mimics reality well, in the sense that the recent crisis was global, and the two parameters, h and ρ_z, which are found to exhibit the most significant structural changes are *not* country-specific parameters.

h, left density @ 2009q1, right density@2008q4

Dashed vertical – median, solid vertical – mode, gray dashed – prior distribution + prior mean

Note: The upper panel displays the evolution of various recursive estimates as a function of time. The lower panel displays the two parameter posterior densities that constitute the structural change. The dark-grey area in the lower panel corresponds to the "area" column value in Table 3.

Source: Own calculation

The elasticity of substitution between domestic and imported consumption goods, η, is the only parameter that implies a significant structural change in both Table 2 and 3. In this case, the time of the change is the onset of the recent economic crisis (2008q2–2009q2) and the shift of the parameter is downward. This change may be explained by households' conservative consumption behaviour during the recession.

The structural change in ψ_2 addresses the domestic monetary authority's preferences towards output growth. This preference falls in the initial stages of the crisis from 0.8 to 0.5, showing that the monetary authority cared less about output growth in this period. The Czech National Bank would have had to lower interest rates more radically for them to be in line with its pre-crisis preference towards output growth, and it chose not to do so.

7. Comparison of Results to Tonner *et al*. (2011)

Direct comparability of this study's results is limited, largely due to the fact that it exa-mines data for the Czech economy. There is only one existing article which deals in depth with parameter changes in a Czech DSGE model. Therein, Tonner *et al*. (2011)

focus on the role of exogenous processes (technologies). The model without technologies demonstrates parameter drifts, whereas the model with technologies has more or less stable parameters. We shall therefore compare results of this paper with those achieved by Tonner *et al.* for the model without technologies.

In their search for structural changes (or parameter drifts), Tonner *et al.* (2011) use a different methodology, and check for the existence of a unit root in the evolution of each parameter's point estimates.

Although Tonner *et al*. (2011) use a much richer model, some of the parameters play a similar role as seen in the model presented in this paper. These parameters are habit formation, Calvo parameter for domestic prices and import prices, preference parameters in domestic monetary rule, and home bias in consumption. Out of these seven comparable parameters, Tonner *et al.* (2011) show results for three – (i) habit formation, (ii) Calvo parameter for import prices, and (iii) home bias in consumption.

Since the null of a unit root in habit formation is not rejected at 10% level, the habit parameter is considered to drift. The change in its point estimate is from approx. 0.932 (in 1996q1) to 0.929 (in 2010), subsequently rising.[8] In our analysis in this paper we have also identified a structural break in habit formation. The change found is much larger (from 0.8 to 0.6, see Table 3) and occurs in one quarter only (whereas Tonner's results indicate a downward drift from 1996 to 2010). Nevertheless, there is a similarity: a downward trend in habit formation during the onset of the recent economic crisis.

Tonner *et al*. (2011) reject parameter drift in the Calvo parameter for import prices at the 1% level. The evolution of this parameter is an oscillation around 0.785, with troughs in 1998 at 0.78, and in 2010 at 0.782. In this paper we reported downward trend for this parameter, from 0.6 to 0.52, however this change is not found to be statistically significant. Both studies therefore concur that there is no statistically significant change in the rigidity of import prices over the period in question.

The third comparable parameter, home bias, has its counterpart in import share in this study.[9] Tonner *et al.* report a drift in home bias at 10% significance level. The parameter oscillates around 0.38, with a trough in 1998 and again in 2011 at 0.32. This study reported a slight increase in the parameter over the whole period under observation, from 0.4 to 0.5, however, this change is not statistically significant. Therefore for the openness of the economy, the two studies report different results.

To conclude the comparison, it could be said that although the approaches for identification of structural changes differ and both studies use quite different DSGE models, the results for comparable parameters show some similarities. Generally, most of the parameter drifts identified in Tonner *et al*. (2011) are continuous upward or downward drifts. On the other hand, most of the structural changes identified in this study are observed in one or more individual quarters. I believe that these differences stem from a richer model formulation in Tonner *et al.* (2011), and from the fact that their estimation was carried out *via* non-linear filtration.

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8   See Tonner *et al.* (2011), Figure 2, p. 521. The parameter values are deduced from the figure since there are no numerical results included.

9   Home bias = 1 – import share.

8. Recursive Impulse Response Analysis

This section illustrates the economic significance of some of identified structural changes and also addresses the question posed by Schorfheide (2008): what if parameters change but respective impulse response functions do not?[10]

I select the period of the recent recession for an exemplary analysis, since there are several structural changes identified in this period and because it may arguably be the most interesting for the reader.

The figures in this section display impulse response functions as a result of an innovation to the system. The value of each innovation is equal to the average standard deviation on the sample of data since 1999. In order to mimic crisis behaviour, all the innovations cause unfavourable shocks. Each figure for the recursive IRFs consists of two panels, which differ only in their angle of view and the number of lags drawn. The bottom left axis "time (end-of-period)" plots the different time frames on which the model was estimated. The impulse response function highlighted in thick red is of special interest to us since it is calculated for the time frame ending in first quarter of 2009, which is the period during which the oncoming recession is most apparent in the data.

Figure 2 | Recursive Impulse Response Functions, Domestic Monetary Shock to Domestic Consumption
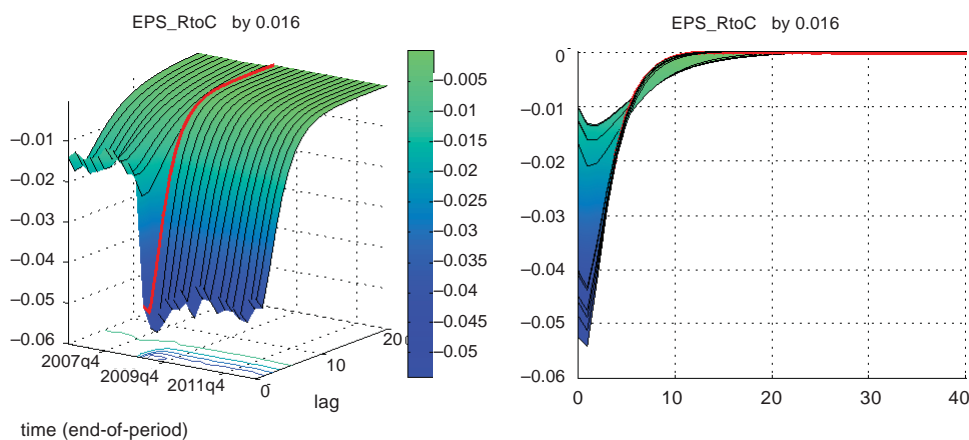


Note: red bold IRF is for 2009q1

Source: Own calculations

Figure 2 displays the IRF for the response of domestic consumption C to domestic monetary policy shock EPS_R. The figure exhibits a drop in households' consumption as a result of higher nominal interest rates. However, the reaction is different in the pre-crisis period, compared with the crisis period and its aftermath. Approximately 2 quarters prior to 2009q1, the trough of the drop in consumption is -0.02. In 2009q1, the reaction is 2.5

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10 This phenomenon is seen in results as reported *e.g.* by Benati and Surico (2009) and Boivin and Giannoni (2002).

times more severe, with a trough below -0.05. In the aftermath of the crisis, the lowest point is below -0.04. This result is partly due to a drop in habit persistence in consumption *h* that occurred in 2009q1 (see discussion to Figure 1).

Figure 3 | Recursive Impulse Response Functions, World-Wide Technology Shock to Foreign Inflation
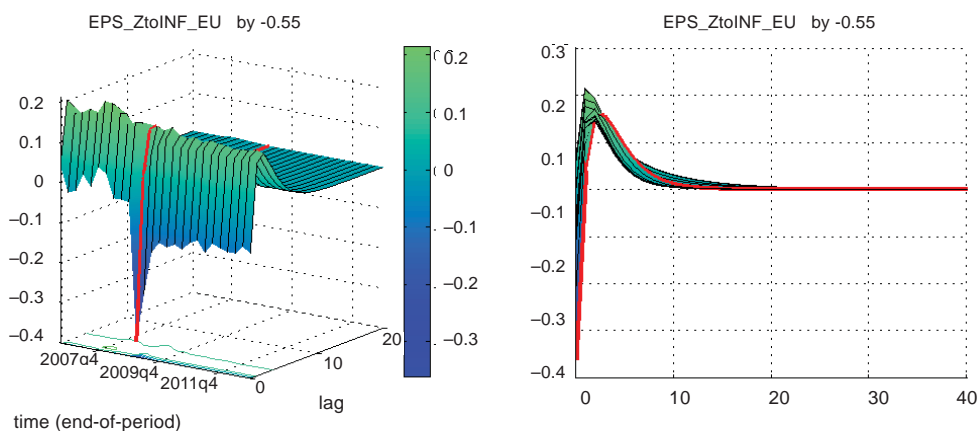
Source: Own calculations

This second example demonstrates the consequences innovation to the world-wide technology shock. In order to mimic the recession, the innovation is negative. Figure 3 displays the reaction of foreign inflation to such a change. Pre-crisis reaction functions show a rise in inflation to some 0.2 and then a decline to a zero steady-state. Post-crisis IRFs begin with a mild deflation followed by convergence as usual. Finally, the "crisis" IRF in 2009q1 (again highlighted in thick red) demonstrates deflation of 0.35 in the first quarter, after which the trajectory is similar to other quarters. This result may have interesting implications for the case of a "favourable" (positive) shock, which would flip over the IRFs, since the indication is therefore that positive technology shock would cause unexpected inflation.

This section has introduced exemplary results for recursive impulse response analysis. The examples show changes in patterns, magnitude, amplitude, and decay. In some cases, the change in the reaction is 3–5 times the change in the original parameter. The first example shown here has direct (monetary) policy implications. The central bank should pay attention to the state of the economy, since *the same* monetary shock can cause much larger drops in consumption and output growth. As for Shorfheide's (2008) question, the examples presented here show that the model for identifying structural changes also identifies changes in impulse response functions in the selected time period.

9. Conclusions

The main goal of this paper is to identify structural changes in the Czech economy approximated by a Dynamic Stochastic General Equilibrium model estimated using Bayesian methods. The time frame of interest spans from 1996 to 2012. Structural changes for this

period have been identified using recursive analysis, (rolling) and the so-called "first observation" analysis. All of these analyses proceeded from a Bayesian estimation of the model.

The first part of the analysis showed that at the beginning of the data sample, namely prior to the first quarter of 1999, there was a structural change that could be mostly attributed to shocks hitting the domestic economy, as well as to the domestic monetary authority's changing preferences. These results can be attributed to the 1997 monetary crisis and its aftermath, together with a switch in the monetary policy to an inflation targeting regime.

Towards the end of the data sample, the results have shown that several parameters changed during the recent economic recession, some of them significantly. It is clear that the first quarter of 2009 is the quarter accompanied by the most changes in the model structure. Moreover, it is also apparent that this period saw shifts in propagation mechanisms. Lower habit persistence in consumption, *i.e.* households not smoothing their consumption as much as they did before the economic crisis, is the most conclusive result found concerning the behaviour of individual economic agents. Also, the domestic central bank lowered its preferences towards output growth during the onset of the recession.

Recursive impulse response analysis has shown that the structural changes carry policy implications, too. During the recent recession, interest rate changes had a much greater impact on economic activity than they had had before the recession. Monetary authorities should therefore be cautious about changing propagation mechanisms during such crises.

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