

## WORKING PAPER SERIES 12

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The Housing Sector over Business Cycles: Empirical Analysis  
and DSGE Modelling



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Jan Brůha, Jiří Polanský

# The Housing Sector over Business Cycles: Empirical Analysis and DSGE Modelling

Jan Brůha and Jiří Polanský \*

## Abstract

In this paper, we analyse the dynamics of the housing sector over business cycles. First, we provide an empirical analysis of the relationships between housing sector data and the main macroeconomic variables both on Czech data and on a sample of advanced economies. We document that in most countries the housing sector co-moves with the rest of the economy. In the past, the Czech housing market showed temporary episodes during which the housing sector was seemingly disconnected, but since 2005 the housing sector has become more cyclical. Second, we develop a cascade of increasingly complex DSGE models to assess the relative merits of each additional mechanism. Contrary to the popular framework with collateral constraints, we concentrate on the housing sector as an additional production sector via the *standard supply and demand mechanisms*. Our results confirm that these standard mechanisms are sufficient to replicate the observed comovements of housing market variables.

## Abstrakt

V tomto článku analyzujeme dynamiku cen nemovitostí určených k bydlení v rámci hospodářských cyklů. Nejprve se zabýváme empirickou analýzou vztahu mezi sektorem nemovitostí určených k bydlení a hlavními makroekonomickými proměnnými v ČR a na vzorku vyspělých ekonomik. Ukazujeme, že ve většině zemí se tento sektor pohybuje souběžně se zbytkem ekonomiky. Česká data ukazují existenci období, v nichž se tento sektor choval nezávisle na zbytku ekonomiky, ale od roku 2005 je více sladěn s hospodářským cyklem. Dále konstruujeme kaskádu dynamických stochastických modelů všeobecné rovnováhy s rostoucí mírou složitosti a posuzujeme relativní význam každého přidávaného mechanismu. Na rozdíl od studií, které se zakládají na finančním omezení, modelujeme sektor nemovitostí určených k bydlení jako další produkční sektor pomocí standardních nabídkových a poptávkových mechanismů. Naše výsledky ukazují, že tento přístup je schopen vysvětlit pozorovaný souběžný vývoj ukazatelů trhu s bydlením.

**JEL Codes:** E32; R21; R31.

**Keywords:** Business cycles; DSGE; housing sector.

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## Nontechnical Summary

The housing sector has become one of the most widely discussed topics in contemporary macroeconomics. Economists are interested in understanding the links between the housing sector and the rest of the macroeconomy and explaining the observed comovements between house prices and macroeconomic aggregates. This paper contributes to this discussion and is composed of two parts.

First, we provide an empirical analysis of the relationships between housing data (house prices, housing production and inputs into the construction sector) and the main macroeconomic variables both on Czech data and on a sample of advanced economies. We document that in most advanced countries the housing sector strongly co-moves with the rest of the economy. In the past, the Czech housing market showed temporary episodes during which the housing sector was seemingly disconnected. Based on the literature, we describe these episodes and argue that one can expect the cyclical properties of the Czech housing market to more closely resemble those of advanced economies in future.

Second, we develop an increasingly complex cascade of DSGE models that incorporate the housing sector. These models are used to assess what is needed to model the housing market. Contrary to the popular framework with collateral constraints, we concentrate on the housing sector as an additional production sector via *standard supply and demand mechanisms*. Our results confirm that these standard mechanisms are sufficient to replicate the observed comovements of housing market variables and we conclude that special features such as collateral-constrained households are not needed to get the model to fit the data. The paper also discusses the relevance of various modelling approaches to fitting and explaining the data, especially the role of the utility function.

## 1. Introduction

Macroeconomic issues associated with the housing sector are among the most widely discussed topics in current macroeconomic analysis. The Great Recession and the associated fall in house prices have intensified this interest. Both academics and policymakers have started to enquire about the links between the housing sector and the rest of the macroeconomy and the underlying causes of the observed comovements between house prices and macroeconomic aggregates. An understanding of these issues will help answer important policy questions such as ‘Do house prices amplify business cycles and should we care strongly about them?’ and ‘Should monetary policy react strongly to booms and busts in house prices?’. The answers to these questions depend on our understanding of the channels between the housing market and the macroeconomy, which means that the macroeconomic linkages of the housing market are of utmost importance.

The objective of this paper is contribute to this important debate. The paper focuses one particular aspect, namely the dynamics of the housing market over the business cycle. There are two main contributions.

The paper starts with an empirical analysis of the comovements between housing sector data and economic activity. We collect data on a sample of advanced countries from two main sources (Eurostat and the Bank for International Settlements) and analyse how various housing sector indicators are related to economic activity over the business cycle. We find that for a typical country, house prices, housing and construction production and inputs into the housing sector are cyclical and slightly more volatile than the output cycle.

We then analyse the Czech housing market data in more detail. We find that some, but not all, housing sector data were disconnected from output dynamics over the business cycle and we identify and discuss specific episodes where this disconnect was most spectacular. Nevertheless, we argue that the alignment of the Czech housing sector with the business cycle has increased over time and we conjecture that the disconnect observed in the earlier period was due to the initial transition conditions and to a specific episode related to EU entry. In that respect, the Czech housing market has recently started to resemble the situation in typical advanced economies, i.e. it has become strongly cyclical.

The second part of the paper is model-based. We ask whether the comovements can be replicated by standard demand and supply factors (such as technology shocks) in a consistent general equilibrium framework. To contribute to this enquiry, we present a cascade of increasingly complex models which explicitly incorporate the housing sector and we compare their performance. The cascade starts with a typical DSGE model carefully calibrated for a small open economy like the Czech Republic. Additional features of the housing sector are added in each extension. We then evaluate the merits of each extension. We conclude with suggestions for modelling the housing sector using DSGE models.

The paper is organised as follows. Section 2 discusses related literature. Section 3 contains the empirical analysis. Section 4 describes the models investigated, while Section 5 describes their properties. The last section 6 concludes. Appendices contain additional materials.

## 2. Literature

As we noted above, understanding housing price determinants seems to be important for central banks. The spectacular fall in house prices before and during the Great Recession caused a surge of interest in this topic. House price fluctuations are associated with business cycle dynamics, and some economists even claim that house prices *are* the business cycle Leamer (2007).

Various approaches have been proposed to explain and model the observed statistical association, and structural macroeconomic models have been built to replicate observed features, to shed light on house price dynamics and to assess the role of policy in mitigating house price fluctuations. We can divide the modelling effort into several streams. One of the most popular macroeconomic approaches is centred on the ground-breaking paper by Iacoviello and Neri (2010), who argue that house price fluctuations, which are the result of preference shocks, contribute in a significant way to economic fluctuations, i.e. that exogenous house prices are the source of business cycles through financial imperfections. The alternative explanations propose that house price fluctuations are merely a *symptom*, rather than a *cause*, of the business cycle, as in Davis and Heathcote (2005). Moreover, expectations about future economic growth are the source of house price dynamics in Kahn (2008) and Tomura (2010). Finally, some papers claim that significant surges and busts in house prices are due to disagreements among agents about fundamentals – see Tomura (2013) and Piazzesi et al. (2007).

The lack of a consensus is unfortunate, as different mechanisms naturally have different implications. If house prices cause business and financial cycles, it is reasonable to consider including them in monetary, or more generally stabilisation, policy objectives, because house price stabilisation would then help to reduce economic fluctuations with all their social costs.

If, however, house prices are a mere symptom of cyclical fluctuations, then it is less obvious why stabilisation policy should react to them. Of course, a situation may arise where house prices threaten, for example, financial stability, and in such case policymakers may react in an appropriate way. But such an idiosyncratic reaction, however appropriate in some situations, is not the same as making house prices part of the systematic policy function.

Finally, if studies asserting that house price fluctuations are caused by behavioural failures (irrationality) are right, house prices should be the domain of financial literacy policy rather than macroeconomic stabilisation policy. Again, under this hypothesis, macroeconomic policymakers may find it necessary to react to house price fluctuations in some special situations, but the response should not consist in changing the systematic part of macroeconomic policy.

For this reason, it is important to analyse the mechanisms underlying the observed relationship between house prices and macroeconomic dynamics.

As stated above, Iacoviello and Neri (2010) is the workhorse of structural macroeconomic models with a housing sector and financial frictions through collateral-constrained households. They develop and estimate a DSGE model with a rich housing sector that contains two important features typical of the housing market. On the supply side, they capture different trends and cyclical properties of house prices and investment relative to other prices and other components of aggregate demand. On the demand side, collateral constraints affect borrowing capacity and allow for spillovers from the housing market to consumer spending. This collateral effect works as follows. In the first phase a rise in house prices increases the value of property as loan collateral, leading to



credit expansion. This expansion increases aggregate demand, which, in turn, fosters a temporary rise in economic activity.

The popularity of the Iacoviello and Neri (2010) framework has resulted in a number of followers who have used this framework to enquire about important monetary policy issues.<sup>1</sup> The empirical relevance of this framework was confirmed by Christensen et al. (2009) on Canadian data. On the other hand, Tonner and Brůha (2014) use the Iacoviello-Neri framework and extend the CNB's g3 core forecasting model. They find that for realistic calibration, house price fluctuations do not have a significant impact on consumption or output. They conclude that for the Czech Republic, the mechanism that links the housing sector with the rest of the economy through the collateral constraint is not important. This is in line with the empirical study by Brůha et al. (2013a).

There are interesting alternatives. For example, Bajari et al. (2013) propose a model with heterogeneous agents to study the interaction between house prices, housing choice and consumption through the life cycle. They find significant evidence for non-separability between consumption and housing in the utility function.

## 2.1 Empirical Studies

Although macroeconomic structural modelling is dominated by models with credit-constrained households (although with the exceptions outlined above), empirical microeconomic studies do not unanimously find support for a credit channel between house price fluctuations and the consumption choice of households.

Campbell and Cocco (2007) on UK data find that although there is a link between the financial market (easing)<sup>2</sup> and house prices (positive effect), they do not confirm the collateral effect of house prices on consumption. Attanasio et al. (2009) provide evidence on UK data that the collateral channel is probably not the source of the comovement between house prices and consumption and identify expectations as the likely cause. This is because the estimated effect is roughly the same for both homeowners and renters, which casts the credit constraint channel in doubt. Likewise, McCarthy and McQuinn (2013) on Irish data find significant responses of consumption to house price shocks, but not through any form of credit constraint.

Cooper (2013) is one of the few empirical papers to report a significant collateral channel, but unlike the above-mentioned studies it does not control for household characteristics (home ownership) and therefore we consider the identification less plausible than the above-mentioned studies.

There has been some interesting research on the relation between the macroeconomy and the housing market in the Czech Republic, too. Hlaváček and Komárek (2011) use econometric analysis to

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<sup>1</sup> For example, Walentin and Sellin (2010) aim at quantifying the role played by housing collateral in the monetary transmission mechanism, specifically the impact of the loan-to-value ratio. They find that the component of the monetary transmission mechanism becomes stronger the higher the loan-to-value ratio is. A change in the maximum loan-to-value ratio from 85% to 95%, all else being equal, implies that the effect of a monetary policy shock is increased by 4% for inflation, 8% for GDP and 24% for consumption. Lambertini et al. (2010) analyse housing market boom-bust cycles driven by changes in households' expectations. They investigate the role of expectations. They find that, in the presence of nominal rigidities, expectations on both the conduct of monetary policy and future productivity can generate housing market boom-bust cycles that resemble data features. Increased access to credit generates a boom-bust cycle in most variables only if it is expected to be reversed in the near future.

<sup>2</sup> This channel has been confirmed by a number of subsequent studies and is intuitive: the decision to buy a house is usually made by young and financially constrained agents, so alleviation of the financial constraints on such agents results in increased demand.

enquire about the macroeconomic determinants of house prices. Brůha et al. (2013a) use a matching estimator to estimate the effect of house price changes on the consumption, savings and indebtedness of households, with an identification strategy based on house ownership and spatial patterns of house price changes. They find little evidence for the effect of house price changes on consumption.

### 3. Empirical Analysis

This part of the paper contains the contribution to analysing the comovements between housing sector data and economic activity. In the first part of this section we carry out the analysis on a set of advanced economies, while the second subsection concentrates on the Czech data. We are mainly concerned with house prices and housing construction quantities and also with labour inputs into the housing sector. On the other hand, we do not discuss wages in the construction sector. This because wages, unlike hours worked or employment, do not display a clear cyclical pattern in most advanced countries (Abraham and Haltiwanger, 1995; Brůha and Polanský, 2015). There are several possible reasons for this, but we do not discuss them here.<sup>3</sup>

#### 3.1 International Data

In this part of the paper, we provide international evidence on the comovement between housing market variables and economic activity using data from advanced countries. We deliberately use a large cross-section of countries since the length of the relevant time series is typically not impressive. If we find that some feature is stable across countries, we can be more certain that this is a genuine feature of market economies, not just an outcome of statistical chance.

Our dataset consists of the following countries: Austria, Belgium, Bulgaria, Croatia, the Czech Republic, Cyprus, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, the UK and the U.S. Our sample starts at 1980Q1 and ends at 2014Q1. Although some countries have data right from 1980, not all countries have all the time series available. We therefore include a particular country in our sample only if it has the relevant time series with a length of at least 12 quarters. For most macroeconomic series, our data come from Eurostat.

First, we investigate the cyclicity of house prices in advanced countries. We therefore compute sample correlations of the cyclical component of output with house prices. We concentrate on the cyclical component from each series since we are interested in business cycle dynamics.<sup>4</sup> It is difficult to obtain good and long house price data series for a large sample of countries. We are aware of two sources: Eurostat and the BIS.<sup>5</sup> The Eurostat data should be methodologically homogeneous<sup>6</sup>, but they have the disadvantage of starting at 2005 for almost all countries. The BIS

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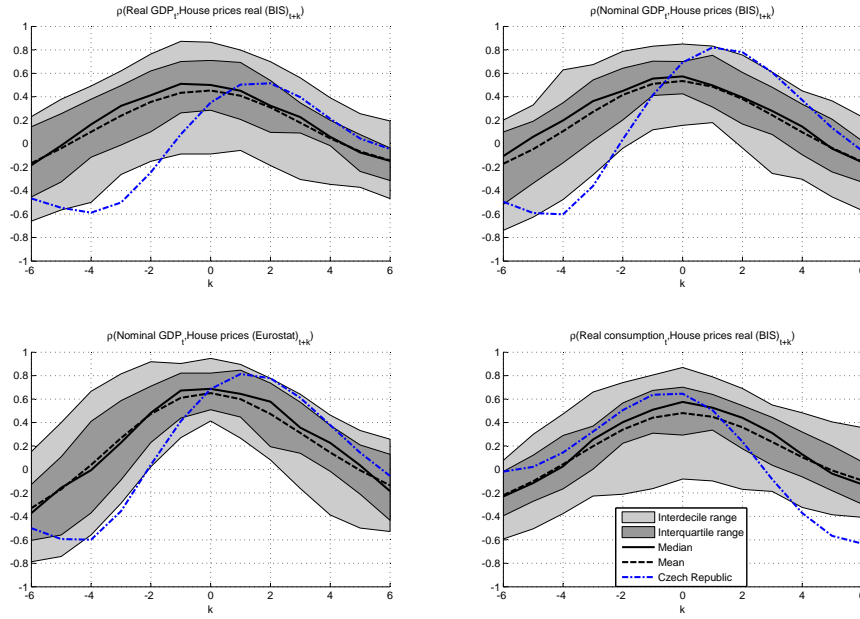
<sup>3</sup> The reader may consult Brůha et al. (2013b), who describe several issues associated with (whole-economy) wages which one should take into account carefully during real-time forecasting. The evolution of average measures can be affected by wage distribution effects or tax optimisation, and we conjecture that these factors may be responsible for hindering wage cyclicity.

<sup>4</sup> By default, we isolate cycles using the Christiano and Fitzgerald (2003) filter. As a robustness check we also consider the Lesser filter (known in macroeconomics also as the Hodrick-Prescott filter (Hodrick and Prescott, 1997) and the results are almost the same. We will be happy to provide details upon request.

<sup>5</sup> Sources: national sources, BIS Residential Property Price database, <http://www.bis.org/statistics/pp.htm>.

<sup>6</sup> See [http://epp.eurostat.ec.europa.eu/cache/ITY\\_SDDS/EN/prc\\_hps\\_esms.htm](http://epp.eurostat.ec.europa.eu/cache/ITY_SDDS/EN/prc_hps_esms.htm) for the data methodology.

**Figure 1: Cyclicity of House Prices**



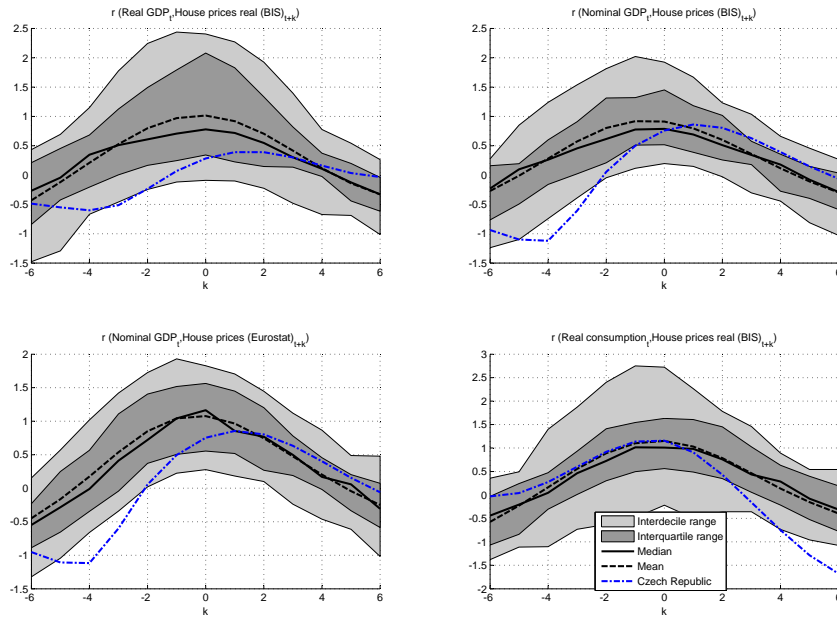
dataset contains longer series for some countries, but the series are not fully harmonised despite serious efforts to choose as similar series as possible from each country. The BIS dataset contains both nominal series and real series (deflated by the CPI), while the Eurostat house price data contain only nominal indices. We therefore compute three types of correlations: (i) the nominal BIS data index versus nominal GDP, (ii) the real BIS data index versus real GDP and (iii) the Eurostat index versus nominal GDP. The results are almost the same for all three types of comparison, which could have been expected as the cyclical dynamics are dominated by real movements. Finally, we consider (iv) the correlation of real house prices with real consumption.

The results can be seen in Figure 1, which shows the correlation of the cyclical component of output with the cyclical components of various house price indices at lags ranging from -6 quarters to 6 quarters. In the figure, we display the mean and median correlations and also the interquartile and interdecile ranges for the cross-section of countries in the sample. Moreover, we display the sample correlation for the Czech data. Apparently, house prices are cyclical. A more detailed analysis based on individual countries reveals that the house price cycle usually lag the output cycle.<sup>7</sup> The Czech Republic is in accordance with the other countries in this respect, as its correlations peak at  $k = 2$  (real variables) or  $k = 1$  (nominal variables).<sup>8</sup>

The correlation of house prices with real consumption usually peaks with the lag of several quarters, and the point estimate of the maximum of this correlation is slightly lower than for the correlation of house prices and output. Our understanding of this finding is that, if nothing else, it does not point to the collateral channel, because if the collateral channel were responsible for the cyclicity of house prices, one would not expect the correlation of consumption with house prices to peak typically *after* the correlation of house prices with output.

<sup>7</sup> To keep the paper as short as possible, we do not present figures for individual countries (except for the Czech Republic). These figures can be provided on request.

<sup>8</sup> This is because the Czech house price data in *both* datasets start in 2005, i.e. the 2002–2004 episode is not included. This issue will be described later.

**Figure 2: Elasticity of House Prices (Cyclical Frequencies)**

Being a measure of cyclicity, the correlations are silent on the relative variances. It may also be revealing to look at the regression coefficient<sup>9</sup> as a measure of the *elasticity* of a variable to the cycle. Elasticity measures how much one variable is *responsive* to movements in another rather than the *intensity* of comovement, which is measured by correlation.<sup>10</sup>

The median (and mean) regression coefficient peaks at 1, which means that in an ‘average’ country, house price cyclical dynamics are volatile to about the same degree as the output cycle. In the Czech Republic, the house price cycle is slightly less volatile than the output cycle, but still, the Czech Republic is not an exceptional country in this regard.

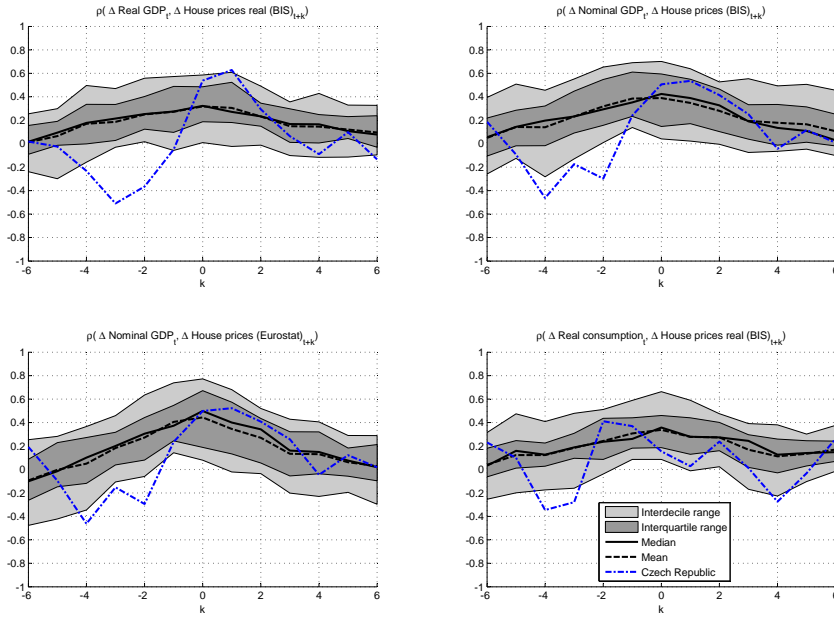
As noted above, all these conclusions remain valid if we use the Lesser-Hodrick-Prescott filter to isolate the cyclical components. The situation is different, however, if we analyse the growth rates. Then, both the cyclicity (correlations) and the elasticity disappear. For the case of correlations, this is illustrated in Figure 3. This phenomenon is caused by the nature of the difference filter, which amplifies the short-run dynamics,<sup>11</sup> i.e. the noise in both series, which, in turn, lowers both measures of interest.

<sup>9</sup> The regression coefficient is defined as  $r_{yx} = \text{cov}(y, x) / \text{var}(x)$  and it is obviously linked to the correlation coefficient  $\rho_{x,y}$  as follows:  $r_{yx} = \sqrt{\text{var}(y) / \text{var}(x)} \rho_{x,y}$ . Hence, for a given correlation, the regression coefficient is high if the variance of  $y$  is high relative to the variance of  $x$ .

<sup>10</sup> One can easily imagine a situation of high correlation and low elasticity (if the movement in one variable is perfectly synchronised with that in the second variable, but the former variable is much less volatile) and a situation of low correlation but high elasticity (if one variable responds strongly to the second one, but is subject to other orthogonal driving forces).

<sup>11</sup> One sometimes encounters objections to the isolation of specific frequencies using linear filters, with the implicit suggestion that growth rates are somehow ‘better’ as they are not subject to ad-hoc filtration. We do not share this view: the differencing of a time series *also* involves the application of a linear filter, which has its own transfer function. And this transfer function rises from zero at frequency  $\omega = 0$  to 2 at frequency  $\omega = \pi$ , which means that it amplifies high frequencies.

**Figure 3: Correlation of Growth Rates of House Prices and Output**



Another important dimension of the data is the output of the construction sector, or more specifically buildings (we are not interested in civil engineering projects). We can also consider other related variables, such construction dwelling permits, which should in principle be a forward-looking indicator. Figure 4 shows the correlation of the volume of constructed buildings<sup>12</sup> and dwelling permits measured both by number and by square metres. For comparison, we also include office permits measured by square metres.<sup>13</sup>

In all countries, including the Czech Republic, the building volume is a cyclical variable. In a typical country, permits and building volumes both lag by one quarter, while in the Czech Republic the lag is about two quarters. In most countries, all these variables are very elastic: the standard errors of the cyclical parts of these variables are usually several times higher than the standard error of the output cycle (see Figure 5). In other words, prices in many countries are more cyclical but less elastic to the cycle than the quantities considered here. Again, one can consider growth rates instead of cyclical components, but as with prices the growth rates are less correlated.

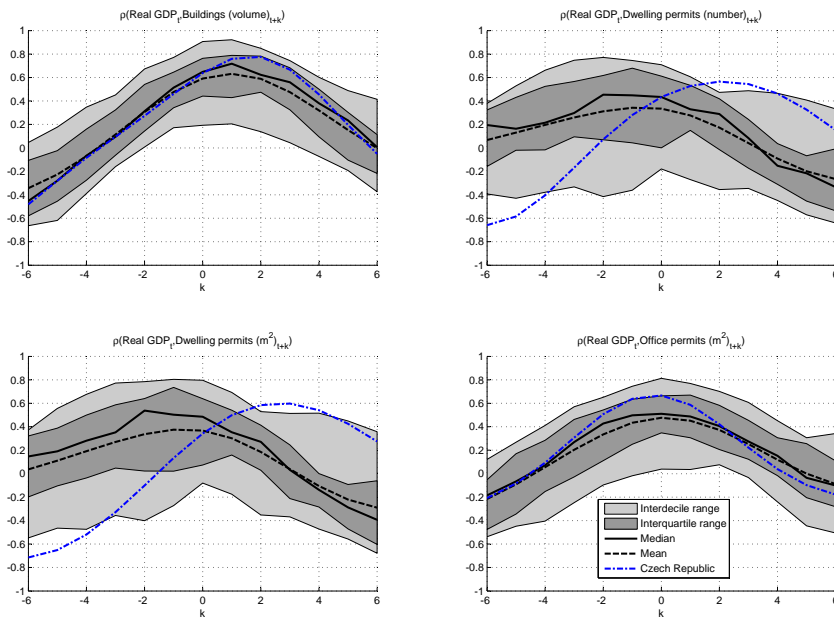
Finally, we look at the correlation of cycles in labour input into construction and output cycles. For the purposes of this paper, it would be nice to have labour inputs going only into house construction, but such data are not available to us. Therefore, we use three measures: (i) persons employed in the subsector of the construction sector related to buildings, (ii) hours worked in the same subsector and (iii) hours worked in the whole of NACE F (construction in the national accounts). For comparison, we also include total hours worked<sup>14</sup> according to the national accounts. The results are presented in Figure 6.

<sup>12</sup> See [http://epp.eurostat.ec.europa.eu/cache/ITY\\_SDDS/EN/sts\\_esms.htm](http://epp.eurostat.ec.europa.eu/cache/ITY_SDDS/EN/sts_esms.htm) for a description of the data.

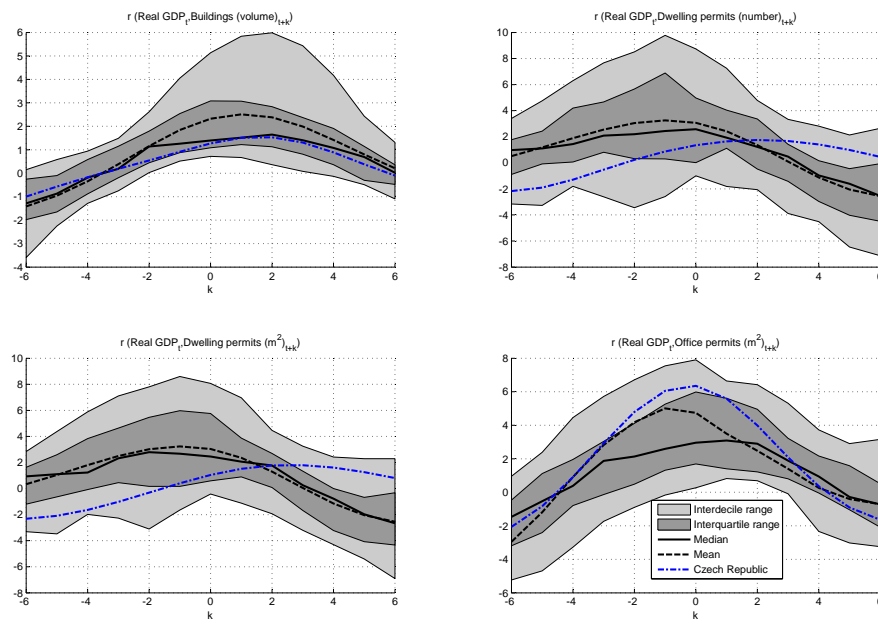
<sup>13</sup> Construction of offices is also a part of building construction, and we are interested in knowing whether office permit dynamics are very different from dwelling permit dynamics to gauge what might be hidden in the dynamics of building volumes.

<sup>14</sup> Brůha and Polanský (2015) and Ohanian and Raffo (2012) find that hours worked are more cyclical than the number of persons employed.

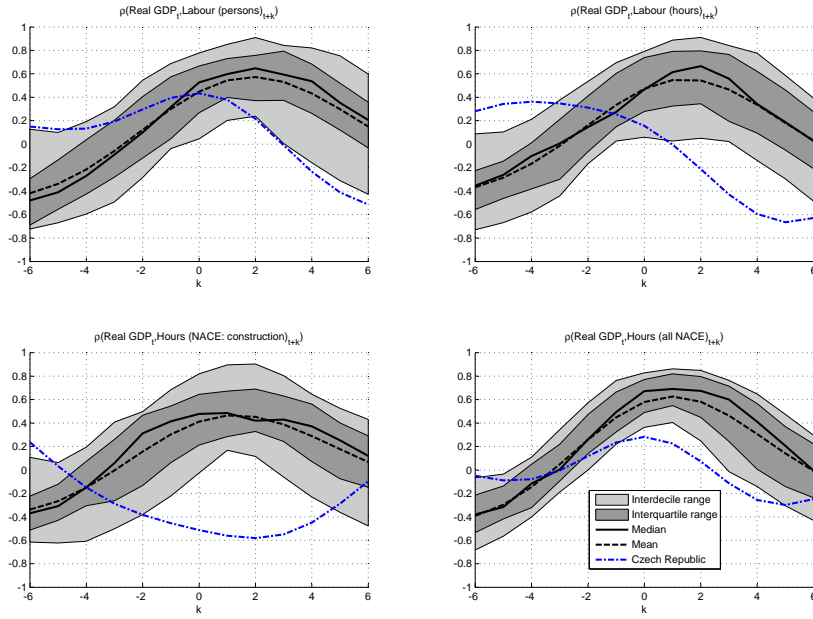
**Figure 4: Correlation of Construction Output and Real Output (Cyclical Frequencies)**



**Figure 5: Elasticity of Construction Output to Output Cycle**



**Figure 6: Correlation of Labour Inputs into Construction Sector and Output (Cyclical Frequencies)**



In a typical country, employment and hours worked in construction as well as total hours worked are cyclical variables, lagging behind the cycle by one or two quarters. In the Czech Republic, labour input into NACE F as a whole is acyclical, due to civil engineering.

In the next subsection, we show that the Czech housing sector data are similar in many respects to what is observed in advanced countries, i.e. they are synchronised at business cycle frequency.

### 3.2 Czech Economy Data

The preceding subsection described the stylised facts for a sample of advanced countries. In this subsection, we concentrate in more detail on Czech data, as for the Czech Republic we were able to collect more detailed and longer time series than those available in international databases.

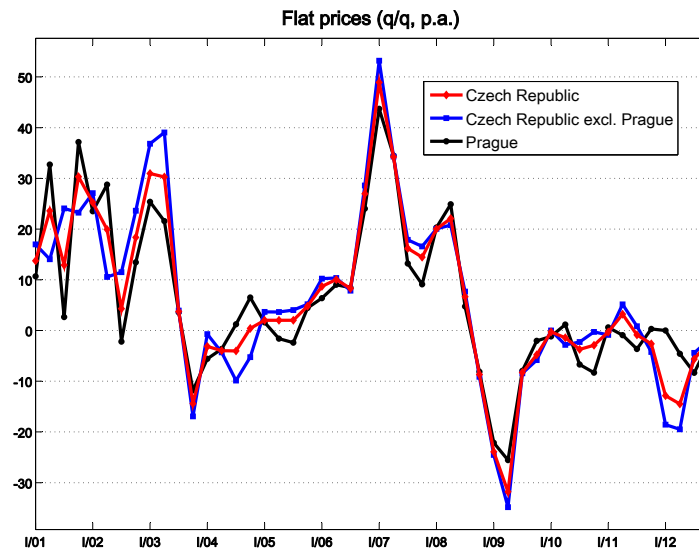
For modelling purposes, we consider it more appropriate to link our model-based house prices to the observed time series of *flat* (apartment) prices rather than *house* prices in the Czech Republic.<sup>15</sup> The reason for this choice is the following: flats are the dominant way of living in larger towns and cities, where their prices should reflect business cycles. House prices, on the other hand, are influenced by several factors which we do not focus on. Examples include demographic factors, job opportunities in rural areas and the development of railways and highways allowing for long-distance commuting.<sup>16</sup> Also, houses in villages and small towns are built by residents who usually plan to live there. Since trade in these houses is not deep, house prices are not subject to business cycles as much as flat prices in cities are.

<sup>15</sup> The international datasets contain an average of the two.

<sup>16</sup> In the Czech Republic in the 1990s, there was a significant surge in demand for new houses on the outskirts of big cities (in satellite villages). We assume that this tendency is no longer dominant, since this type of ‘commuter’ has started to again prefer smaller towns with good public transport connections and public services.

Figure 7 depicts the quarter-on-quarter per annum (q/q, p.a.) growth rate of flat prices for the whole economy and for the economy excluding Prague, and of flat prices in Prague. The evolution (and thus the economic story) of each time series is similar in all cases, allowing us to choose the whole economy index as our observable for house prices.

**Figure 7: Flat Prices (q/q, p.a.)**



The evolution of flat prices can be divided into several historical episodes. First, the beginning of the series shows relatively high (although volatile) growth in flat prices, followed by a drop in 2003. The significant rise in flat prices in 2002 is often attributed to expectations of increased demand for apartments after the Czech Republic's expected entry into the European Union in May 2004 (see Hlaváček and Komárek, 2009). The popular story then continues that during 2003, when it became clear that there would no massive inflow of EU citizens into the Czech Republic, flat prices decreased sharply. Thus, the data may contain an irrational surge in house prices (an irrational bubble) which was pricked in 2003.

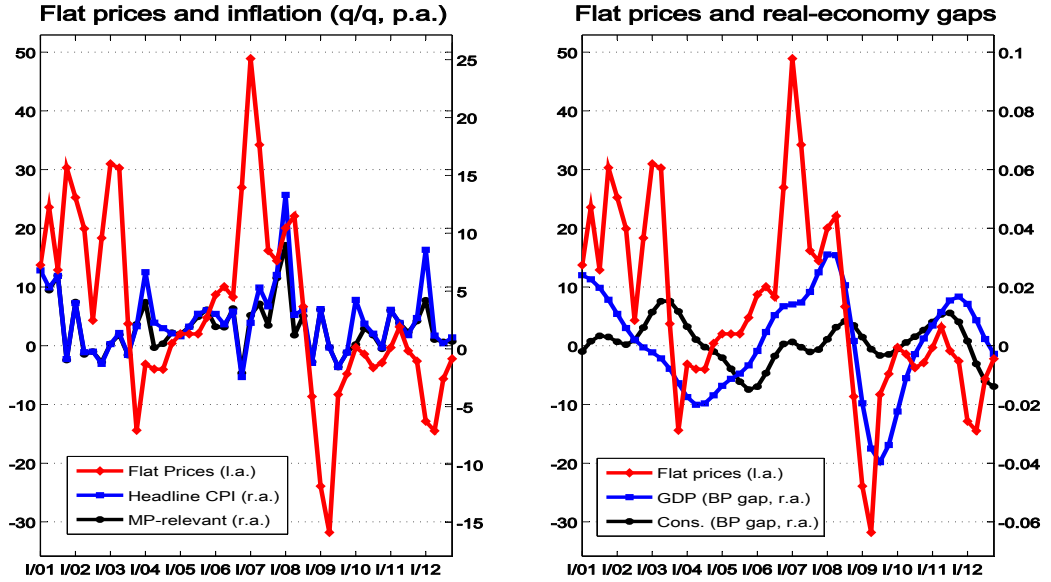
Second, the 2004–2006 period is characterised by a gradual recovery of flat prices. This was followed by a steep increase in 2006–2007. The growth of flat prices stayed high during the first half of 2008, maybe reflecting the significant economic boom the Czech economy was undergoing at the time. The developments in 2007 and 2008 are sometimes referred to as a bubble (see Hlaváček and Komárek, 2011) due to the magnitude of the increase. And third, the Great Recession caused a deep slump in flat prices. From 2010 onwards, flat prices are (on average) decreasing, possibly waiting for a recovery of the Czech economy.

In Figure 8 we compare flat prices in the Czech economy with inflation and real-economy gaps. Flat prices (on the left-hand axis) are much more volatile than headline and monetary policy-relevant inflation (both on the right-hand axis). Moreover, their comovement is not strong. In the right panel, we compare flat prices (on the left-hand axis) with the GDP and consumption cycles (both on the right-hand axis). We interpret the evidence in the figures as follows: first, the comovement between flat prices and the GDP gap is strong. This may indicate that flat prices in the Czech



economy reflect the cycle and demand-driven factors. Second, despite this comovement, flat prices decoupled from GDP in 2002–2003, possibly indicating a bubble. Third, the comovement between flat prices and consumption is less strong than that between flat prices and GDP. This does not support the existence of strong wealth channels.

**Figure 8: Comovement of Flat Prices with Inflation and Real-Economy Gaps**



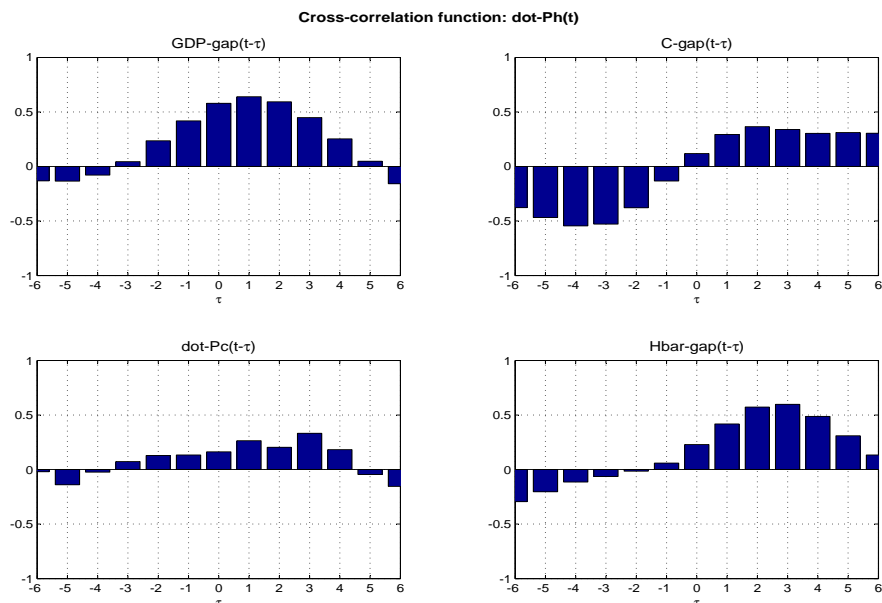
To sum up, prior to 2005 house prices were driven by forces other than cyclical fluctuations alone. Since 2010, prices have been more aligned with the cycle.

As a measure of volumes in the Czech Republic we choose the time series of construction production in the housing sector. In general, we want a variable which captures the dynamics of new house construction or investment in the housing sector. This is the main reason why we are not interested in linking the housing stock implied by the model to some observed counterpart. Due to the high possible uncertainty and difficulty in measuring the housing stock in an economy, we focus on construction production, which should bear more information about business cycles. This is equivalent to the investment-capital law of motion in production sectors.

Figure 9 shows the correlation histogram of flat prices (dot-Ph) with the GDP gap, the consumption gap (C-gap), MP-relevant inflation (dot-Pc) and the housing construction gap (Hbar-gap).<sup>17</sup> The figure shows a relatively significant correlation between flat prices and the business cycle (the GDP gap). The correlation between flat prices and inflation or the consumption gap is negligible.<sup>18</sup> These panels confirm that flat prices reflect business cycles and do not indicate significant wealth effects in the Czech economy. The last panel shows that housing construction lags behind prices. This can be partly explained by the fact that construction investment is linked more strongly with GDP.

<sup>17</sup> The gaps are acquired using the band pass filter (Christiano and Fitzgerald, 2003) at 6–32 quarter frequency. As a check, we use the HP filter (Hodrick and Prescott, 1997) with the standard value for the smoothing parameter ( $\lambda = 1,600$ ), which gives similar results.

<sup>18</sup> The high negative correlation in the four-period lag is probably caused by a previous cycle.

**Figure 9: Correlation of Flat Prices with Inflation and Real-Economy Gaps**

Figures 10 and 11 present a detailed inspection of construction production. The comovement (the third panel in 10) between housing construction and economic activity is relatively strong, except in 2003–2004. Moreover, construction lags behind the GDP gap in 2006–2009, but evolves contemporaneously from 2010 onwards. This can be explained by the rapid increase in housing construction in 2006, when the Czech business cycle (then in a boom phase) switched to a more robust position. As the impact of the recession was not anticipated in real time, the lag of housing construction in 2009 can be explained by construction firms' expectations of a rapid return to economic growth and also probably by the fact that it was less costly to finish some construction projects than to stop them. Since 2010, construction developers seem to have been careful to follow the business cycle.<sup>19</sup> Figure 11 presents the correlation between the housing construction gap and several variables and shows that housing construction lags behind the GDP gap, does not co-move strongly with the consumption gap and MP-relevant inflation, and also lags behind house prices.

All in all, although the housing market has become cyclical, the correlations between housing market variables and macro aggregates are not always impressive even at business cycle frequencies. We argued that the relatively low correlations (compared to advanced countries) may be due to short time series that are contaminated by the particular episode of 2002–2004 (see above for a discussion). Nevertheless, we still think that the housing market dynamics are dominated by standard demand and supply effects that can be related to the real economy. Moreover, given the recent developments, we consider it likely that the Czech housing sector will move closer to the cyclical patterns observed in advanced countries.

<sup>19</sup> The latest development (change in behaviour) is one of the reasons why we do not incorporate time-to-build housing investment (Kydland and Prescott, 1982) into the model described in the next sections.

Figure 10: Housing Construction

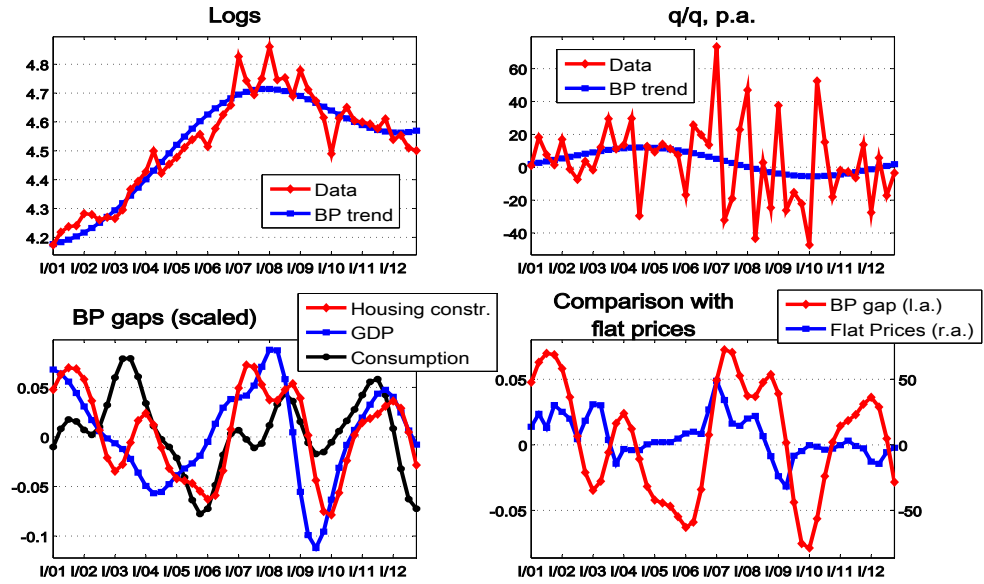
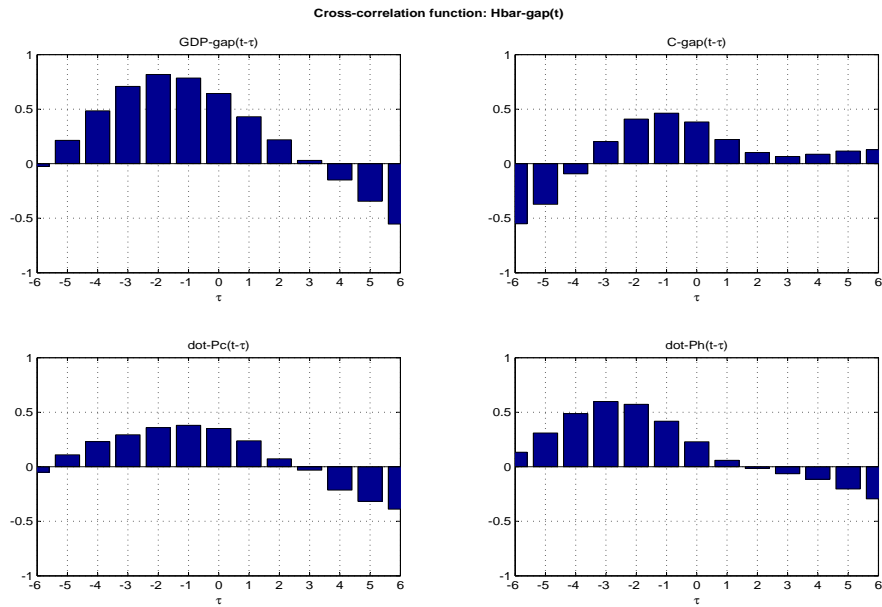


Figure 11: Correlation of Housing Construction with Real-Economy Gaps and Flat Prices



## 4. Models

In this section, we introduce a cascade of DSGE models containing the housing sector. To keep the analysis concise, we focus mainly on the motivation behind the model structures, our assumptions, and subsequent optimisation problems. The first-order conditions can be found in Appendix A. We start with the baseline framework without the housing sector and then continue with several model extensions in the next subsections. The complexity of the models gradually increases.<sup>20</sup>

The notation of the models is as follows:

- Bars denote economy-wide variables, which are considered to be exogenous from the perspective of optimising households and firms. We therefore refrain from using indices for the continua of monopolistic competitive households and firms in order to provide a more lucid description of the model. All individual households and firms are assumed to be too small to affect aggregate variables.
- All models are derived up to the first order, then a symmetric equilibrium is assumed, e.g.  $\bar{C}_t = C_t$  for aggregate consumption.
- Dots over variables denote quarter-on-quarter (q/q) growth rates.
- Tildes over variables denote denomination in foreign currency.

### 4.1 Baseline Model

The baseline framework (Figure 12) is inspired by the g3 model (Andrle et al., 2009) in terms of its overall structure and some important features. We consider this framework to be suitable for modelling the Czech economy, and it can thus be used as a starting framework for the housing sector extensions.<sup>21</sup> Although our baseline model is rather simpler than g3, i.e. it does not contain regulated prices, quality of goods and so on, it inherits most importantly g3's balanced growth path with long-run real exchange rate appreciation and export-specific and openness technologies. These features are important for capturing Czech stylised facts and also significantly reduce the drifting of structural parameters due to structural changes and the ongoing convergence process of the Czech economy (Tonner et al., 2011). Also, the model contains a cascade of nominal rigidities within its production structure, which, together with local currency pricing, implies multiple stages of gradual exchange rate pass-through (Andrle et al., 2009).

#### 4.1.1 Households

Households consume, make investment decisions, supply differentiated labour, rent capital and trade domestic government bonds. Also, they own all firms in the domestic economy and thus receive dividends (or finance those firms internally).

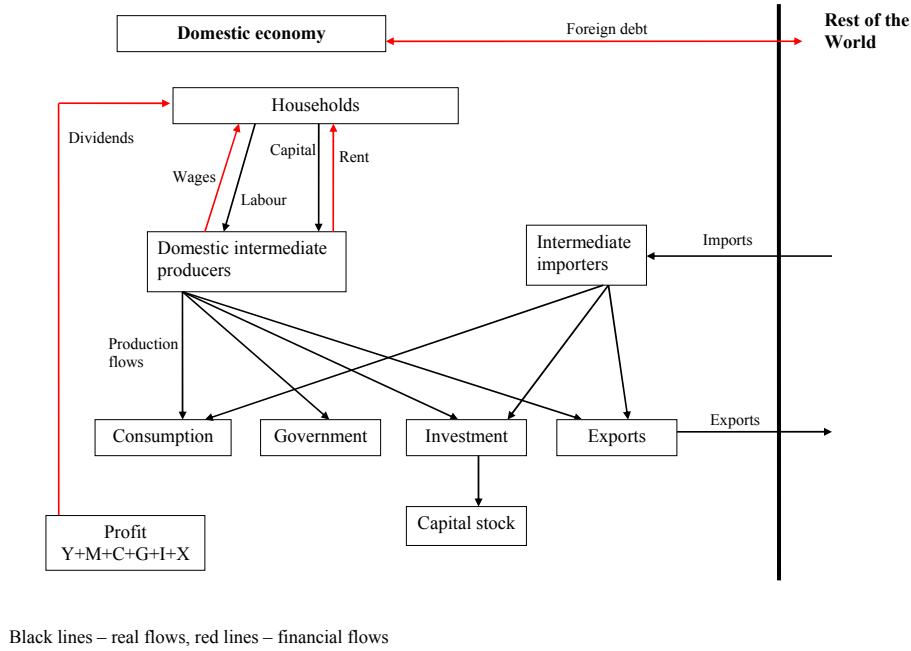
Formally, they maximise a utility function separable in logarithmic consumption with external habit formation (Abel, 1990) and linear leisure (Hansen, 1985) subject to the budget constraint and a

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<sup>20</sup> Although we analyse a different topic, we are inspired by the structure of the paper by Schmitt-Grohé and Uribe (2003).

<sup>21</sup> The model has also proved itself to be useful for regular forecasting during turbulent times such as the Great Recession (Brůha et al., 2013b).

Figure 12: Model Structure – Baseline



downward-sloping labour demand curve:<sup>22</sup>

$$\begin{aligned} \max_{C_t, B_t, I_t, K_t, L_t, W_t} \mathbb{E}_0 \sum_{t=0}^{\infty} \left( \prod_{\tau=0}^t \beta_{\tau} \right) & \left\{ (1 - \chi) \log(C_t - \chi \bar{C}_t^F) + \phi_L a_t^L (1 - L_t) \right. \\ & - \lambda_t \left[ P_t^C C_t + P_t^I I_t + B_t - W_t L_t - R_{t-1} B_{t-1} - Q_t K_{t-1} - P_t^C T_t - \Phi_t \right. \\ & \left. \left. + \lambda_t^K \left[ K_t - K_{t-1}^{1-\delta_K} \left( \frac{I_t}{\delta_K} \right)^{\delta_K} + \frac{\eta_K}{2} \left( \frac{I_t}{I_{t-1}} \frac{1}{\alpha \alpha^I} - 1 \right)^2 K_{t-1} \right] \right] \right\}, \end{aligned}$$

where  $\mathbb{E}_0$  is an expectations operator conditional on the information available up to period 0,  $C_t$  is real consumption,  $\bar{C}_t^F \equiv \exp(\varepsilon_t^C) \bar{C}_{t-1}$  denotes external habit formation with habit (demand) shocks  $\varepsilon_t^C$ ,  $I_t$  is real investment,  $K_t$  is the capital stock,  $B_t$  denotes domestic government bonds,  $L_t$  denotes hours worked,  $W_t$  is the nominal wage,  $R_t$  is the domestic interest rate,  $Q_t$  denotes rent from capital,  $P_t^C$  is the consumption deflator,  $P_t^I$  is the price of investment,  $T_t$  denotes lump-sum transfers,  $\Phi_t$  denotes dividend payments,  $\lambda_t$  is the shadow price of wealth,  $\lambda_t^K$  is the price of capital,<sup>23</sup>  $a_t^L$  is a temporary process for labour supply shocks,  $\beta_{\tau}$  is the discount factor,  $\chi$  is a habit formation parameter,  $\phi_L$  is a parameter scaling hours worked in the utility function,  $\delta_K$  denotes the capital depreciation rate,  $\eta_K$  is an investment adjustment costs parameter,  $\alpha$  is the long-run aggregate growth of the economy and  $\alpha^I$  determines the long-run growth of real investment.

<sup>22</sup> The Calvo-Yun setup (Calvo, 1983; Yun, 1996) with a full indexation scheme for Phillips curve derivation is used for all monopolistically competitive sectors in all models. During model development, we also used a setup with quadratic costs of price adjustment (Rotemberg, 1982a,b; Beneš et al., 2009), which yielded similar dynamics.

<sup>23</sup> Note that the law of motion of capital is inserted into the budget constraint.

The downward-sloping labour demand is

$$L_t = \left( \frac{W_t}{\bar{W}_t} \right)^{-v_w} \bar{L}_t,$$

where  $v_w$  is the elasticity of substitution among differentiated labour types.

#### 4.1.2 Domestic Intermediate Firms

There is a continuum of domestic intermediate producers. Using hired labour and rented capital from households, firms produce differentiated intermediate goods, which are used consecutively in the next stage of production (final-goods sectors).

Domestic intermediate producers minimise their costs subject to the Cobb-Douglas production technology

$$\min_{k_t, L_t} \mathbb{E}_0 \sum_{t=0}^{\infty} \left( \prod_{\tau=0}^t \beta_{\tau} \frac{\lambda_t}{\lambda_0} \right) \left[ Q_t k_t + W_t L_t + q_t^Y (Y_t - a_t^Y k_t^{1-\gamma_L} (A_t L_t)^{\gamma_L}) \right],$$

where  $Y_t$  is domestic intermediate output,  $a_t^Y$  denotes total factor productivity (TFP),  $k_t$  is the capital stock substituted into period  $t$ , i.e.  $k_t \equiv K_{t-1}$ ,  $q_t^Y$  denotes nominal marginal costs in intermediate production,  $A_t$  is labour-augmenting technology,<sup>24</sup>  $\gamma_L$  denotes the share of labour in production and  $\prod_{\tau=0}^t \beta_{\tau} \frac{\lambda_t}{\lambda_0}$  is the nominal pricing kernel.<sup>25</sup>

Also, domestic intermediate firms maximise their profits subject to the downward-sloping demand curve and the Calvo-Yun setup with a full indexation scheme:

$$\max_{Y_t, P_t^Y} \mathbb{E}_0 \sum_{t=0}^{\infty} \left( \prod_{\tau=0}^t \beta_{\tau} \frac{\lambda_t}{\lambda_0} \right) \left[ P_t^Y Y_t - q_t^Y Y_t \right],$$

where  $P_t^Y$  is the price of domestic intermediate goods. The downward-sloping demand curve is

$$Y_t = \left( \frac{P_t^Y}{\bar{P}_t^Y} \right)^{-v_y} \bar{Y}_t,$$

where  $v_y$  is the elasticity of substitution among differentiated domestic intermediate products.

#### 4.1.3 Intermediate Importers

A continuum of importers costlessly differentiate a single foreign bundle.<sup>26</sup> Due to the local currency pricing, imported goods are sticky in the domestic currency.

<sup>24</sup> The two technology shocks are allowed to have different persistence. Introducing labour-augmenting (Harrod-neutral) technology is necessary to ensure a balanced growth path of the model (Barro and Sala-i-Martin, 2004).

<sup>25</sup> Since firms are owned by households, the firms' discount factor contains the marginal utility of real wealth (Dib, 2001). Andrieu et al. (2009) define a kernel between periods  $s$  and  $t$  as  $\beta^{s-t} \frac{\lambda_s}{\lambda_t}$ . Since  $\beta$  is not a constant in our case, the kernel is modified to  $\prod_{\tau=t+1}^s \beta_{\tau} \frac{\lambda_s}{\lambda_t}$ .

<sup>26</sup> Following Andrieu et al. (2009), there is a continuum of countries in the world, where one of them is the home country. In the first step, a continuum of exporters in each country compete only within their own country, which results in a single bundle from each country. In the second step, an international bundler packs all these bundles together into a single good, which is subsequently differentiated costlessly by a continuum of importers in each country.

Importers maximise their profits analogously to domestic intermediate-goods producers, i.e.

$$\max_{M_t, P_t^M} \mathbb{E}_0 \sum_{t=0}^{\infty} \left( \prod_{\tau=0}^t \beta_{\tau} \frac{\lambda_t}{\lambda_0} \right) [P_t^M M_t - P_t^* M_t],$$

where the downward-sloping demand curve and the indexation scheme are analogous to the previous case. Nominal marginal costs  $P_t^*$  are world prices in the domestic currency.

#### 4.1.4 Consumption Goods-Producing Firms

Each consumption goods-producing firm uses domestic and imported intermediate inputs via Leontief technology.<sup>27</sup> Each firm minimises its costs of production

$$\min_{Y_t^C, M_t^C} \mathbb{E}_0 \sum_{t=0}^{\infty} \left( \prod_{\tau=0}^t \beta_{\tau} \frac{\lambda_t}{\lambda_0} \right) \left[ P_t^Y Y_t^C + (P_t^M A_t^X)(M_t^C / A_t^X) - q_t^C \left( C_t - \min \left( \frac{Y_t^C}{1 - \omega_C}, \frac{(M_t^C / A_t^X)}{\omega_C} \right) \right) \right],$$

where  $Y_t^C$  and  $M_t^C$  are domestic and imported intermediate goods, which are used for the production of consumption goods, and  $A_t^X$  is export-specific technology, which makes the use of imported goods less productive and more expensive (Andrle et al., 2009).

Profit maximisation (price setting) is analogous to other production sectors. Firms in each final goods-producing sector are monopolistically competitive and face a downward-sloping demand curve with a full indexation scheme

$$\max_{C_t, P_t^C} \mathbb{E}_0 \sum_{t=0}^{\infty} \left( \prod_{\tau=0}^t \beta_{\tau} \frac{\lambda_t}{\lambda_0} \right) [P_t^C C_t - q_t^C C_t].$$

#### 4.1.5 Government Goods-Producing Firms

Government goods-producing firms use only domestic intermediate goods for their production purposes. The production technology is

$$G_t = Y_t^G,$$

where  $G_t$  denotes real government consumption and  $Y_t^G$  is the part of domestic intermediate production used for the production of government goods.

Profit maximisation is of the same form as in previous cases, i.e.

$$\max_{G_t, P_t^G} \mathbb{E}_0 \sum_{t=0}^{\infty} \left( \prod_{\tau=0}^t \beta_{\tau} \frac{\lambda_t}{\lambda_0} \right) [P_t^G G_t - q_t^G G_t],$$

where the downward-sloping demand curve is analogous to that for other final goods-producing sectors.

<sup>27</sup> Using CES production technology instead of the Leontief function does not have any significant effects on the behaviour or performance of the models.

#### 4.1.6 Investment Goods-Producing Firms

The investment goods-producing sector faces similar optimisation problems to consumption goods-producing firms, i.e.

$$\min_{Y_t^I, M_t^I} \mathbb{E}_0 \sum_{t=0}^{\infty} \left( \prod_{\tau=0}^t \beta_{\tau} \frac{\lambda_t}{\lambda_0} \right) \left[ P_t^Y Y_t^I + (P_t^M A_t^X)(M_t^I / A_t^X) - q_t^I \left( I_t - \min \left( \frac{Y_t^I}{1 - \omega_I}, \frac{(M_t^I / A_t^X)}{\omega_I} \right) \right) \right]$$

and

$$\max_{I_t, P_t^I} \mathbb{E}_0 \sum_{t=0}^{\infty} \left( \prod_{\tau=0}^t \beta_{\tau} \frac{\lambda_t}{\lambda_0} \right) [P_t^I I_t - q_t^I I_t].$$

#### 4.1.7 Export Goods-Producing Firms

As for the consumption and investment sectors, final export goods are produced from both domestic and imported intermediate goods. Due to local currency pricing, export prices are sticky in the foreign currency

$$\min_{Y_t^X, M_t^X} \mathbb{E}_0 \sum_{t=0}^{\infty} \left( \prod_{\tau=0}^t \beta_{\tau} \frac{\lambda_t}{\lambda_0} \right) \left[ P_t^Y Y_t^X + (P_t^M A_t^X)(M_t^X / A_t^X) - q_t^X \left( X_t - \min \left( \frac{Y_t^X}{1 - \omega_X}, \frac{(M_t^X / A_t^X)}{\omega_X} \right) \right) \right]$$

and

$$\max_{X_t, \tilde{P}_t^X} \mathbb{E}_0 \sum_{t=0}^{\infty} \left( \prod_{\tau=0}^t \beta_{\tau} \frac{\lambda_t}{\lambda_0} \right) [\tilde{P}_t^X X_t - q_t^X X_t].$$

#### 4.1.8 Forex Dealers

The UIP equation is derived under the assumption that foreign bond traders face quadratic trading costs, i.e.

$$\max_{B_t^*} \mathbb{E}_0 \left[ \left( \prod_{\tau=0}^t \beta_{\tau} \frac{\lambda_t}{\lambda_0} \right) S_{t+1} B_t^* R_t^* - S_t B_t^* - S_t \frac{\zeta}{2} \mathfrak{S}_t^{uip} (B_t^*)^2 \right],$$

where  $S_t$  is the nominal exchange rate,  $B_t^*$  denotes foreign government bonds,  $R_t^*$  is the foreign interest rate and  $\zeta$  is a parameter governing trading costs denoted by  $\mathfrak{S}_t^{uip}$ .

#### 4.1.9 Monetary and Fiscal Policy

The central bank targets year-on-year inflation four periods ahead via open market operations

$$\log R_t = \rho_R \log R_{t-1} + (1 - \rho_R) \left[ \log R + \psi \log \left( \frac{\dot{P}_{t+4}^{yy}}{\dot{P}_{yy}} \right) \right] + \varepsilon_t^{mp},$$



where  $\frac{\hat{P}_{t+4}^{yy}}{\hat{P}_{yy}}$  is the deviation of year-on-year inflation four periods ahead from the target,  $\rho_R$  is the parameter governing interest rate smoothing and  $\psi$  is the weight on the deviation from the target capturing the reactivity of the central bank. As the model contains the national accounts, the consumption deflator appears in equation (A.1). To simplify the framework we assume that the consumption deflator equals the CPI in each period.

Fiscal policy is Ricardian. Nominal government consumption is linked to nominal private consumption

$$\log \left( \frac{P_t^G G_t}{P_t^C C_t} \right) = \rho_G \log \left( \frac{P_{t-1}^G G_{t-1}}{P_{t-1}^C C_{t-1}} \right) + (1 - \rho_G) \log \left( \frac{P_t^G G_t}{P_t^C C_t} \right) + \varepsilon_t^G.$$

## 4.2 Extension I: Houses Fall from the Sky

First, we capture a hypothetical situation in which the quantity of houses is exogenous – as if houses fall from the sky. Such a framework, although unsuitable for practical purposes (historical filtration and forecasting), can be considered a very first confrontation with real house price data. Of course, such a model does not contain a mechanism for explaining volumes.

Compared with the baseline model, households have direct utility from ownership of houses.<sup>28</sup> Also, households can trade their houses (the equilibrium, of course, implies zero net trade). The structure of the model is presented in Figure 13, where the green lines depict flows associated with the housing sector.

We index utility from houses using parameter  $\eta$ , which can vary from 0 to infinity. By manipulating this parameter, one can model different situations, such as housing as a luxury or inferior good relative to non-durable consumption:

$$\begin{aligned} \max_{C_t, B_t, I_t, K_t, L_t, W_t, H_t} \mathbb{E}_0 \sum_{t=0}^{\infty} \left( \prod_{\tau=0}^t \beta_{\tau} \right) & \left\{ (1 - \chi) \log(C_t - \chi \bar{C}_{t-1}^F) + \frac{\phi_H \exp(\varepsilon_t^H) H_t^{1-\eta}}{1 - \eta} + \phi_L a_t^L (1 - L_t) \right. \\ & - \lambda_t \left[ P_t^C C_t + P_t^I I_t + B_t + \lambda_t^H H_t - W_t L_t - R_{t-1} B_{t-1} - \lambda_t^H H_{t-1} - Q_t K_{t-1} - P_t^C T_t - \Phi_t \right. \\ & \left. \left. + \lambda_t^K \left[ K_t - K_{t-1}^{1-\delta_K} \left( \frac{I_t}{\delta_K} \right)^{\delta_K} + \frac{\eta_K}{2} \left( \frac{I_t}{I_{t-1}} \frac{1}{\alpha \alpha^I} - 1 \right)^2 K_{t-1} \right] \right] \right\}, \end{aligned}$$

where  $H_t$  denotes the stock of houses,  $\varepsilon_t^H$  is a housing preference shock,  $\lambda_t^H \equiv P_t^H$  is the price of the housing stock,<sup>29</sup>  $\phi_H$  is a scaling parameter and  $\eta$  is the utility curvature with respect to the stock of houses.

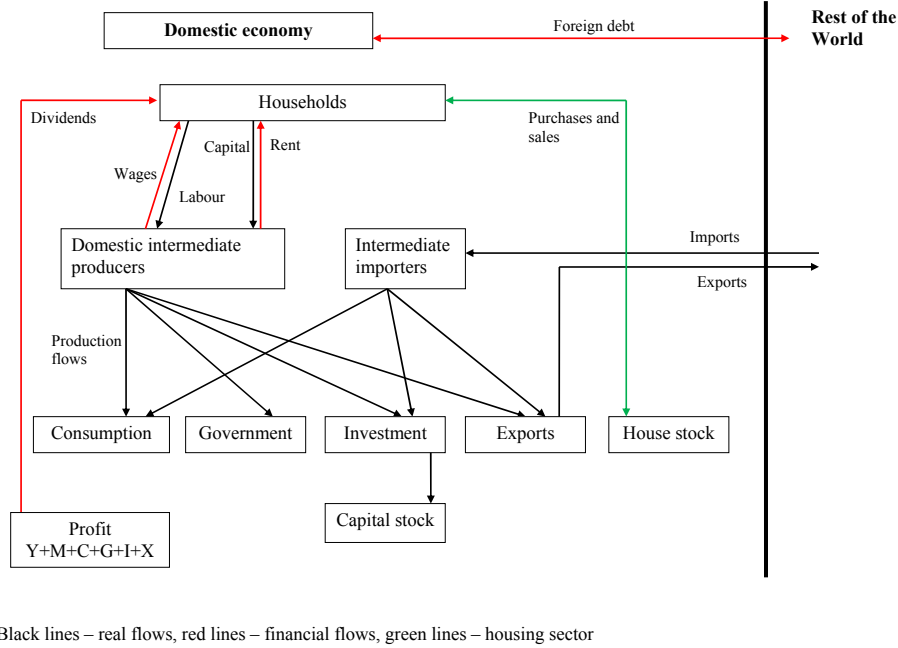
The process for the amount of houses is an exogenous AR(1) defined as follows:

$$\log H_t = \rho_H \log H_{t-1} + (1 - \rho_H) \log H + \varepsilon_t^{\mathcal{H}},$$

where  $\rho_H$  is an autoregressive parameter and  $\varepsilon_t^{\mathcal{H}}$  is the exogenous shock.

<sup>28</sup> Throughout the paper, we do not distinguish between houses and flats and denote their volume as ‘houses’, ‘the stock of houses’ or ‘the housing stock’.

<sup>29</sup> We denote house prices by  $\lambda_t^H$  (instead of  $P_t^H$ ) to be compatible with the rest of the housing sector models presented in the next subsections.

**Figure 13: Model Structure – Houses Fall from the Sky**

### 4.3 Extension II: Houses Are Produced from Intermediate Output

In the second extension, we assume that new houses are produced from domestic intermediate output. As in other production sectors in the model(s), new house-producing firms are monopolistically competitive and owned by households. After new houses are produced, they become a part of the housing stock  $H_t$  (via the law of motion), which enters the utility function in the same way as in the previous model. Also, households do not trade or rent the stock of houses. The structure of the model is shown in Figure 14.

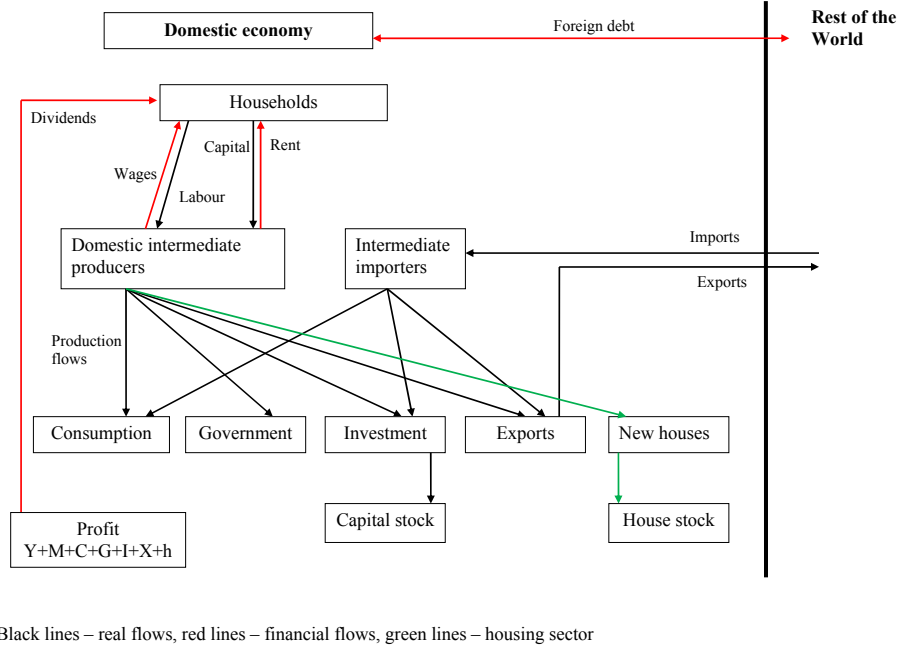
#### 4.3.1 Households

The optimisation problem of households is

$$\begin{aligned} \max_{C_t, B_t, I_t, K_t, L_t, W_t, H_t, \hat{h}_t} \mathbb{E}_0 \sum_{t=0}^{\infty} \left( \prod_{\tau=0}^t \beta_{\tau} \right) & \left\{ (1-\chi) \log(C_t - \chi \bar{C}_t^F) + \frac{\phi_H \exp(\varepsilon_t^H) H_t^{1-\eta}}{1-\eta} + \phi_L a_t^L (1-L_t) \right. \\ & - \lambda_t \left[ P_t^C C_t + P_t^I I_t + B_t + P_t^{\hat{h}} \hat{h}_t - W_t L_t - R_{t-1} B_{t-1} - Q_t K_{t-1} - P_t^C T_t - \Phi_t \right. \\ & \quad \left. + \lambda_t^K \left[ K_t - K_{t-1}^{1-\delta_K} \left( \frac{I_t}{\delta_K} \right)^{\delta_K} + \frac{\eta_K}{2} \left( \frac{I_t}{I_{t-1}} \frac{1}{\alpha \alpha^I} - 1 \right)^2 K_{t-1} \right] \right. \\ & \quad \left. \left. + \lambda_t^H \left[ H_t - H_{t-1}^{1-\delta_H} \left( \frac{\hat{h}_t}{\delta_H} \right)^{\delta_H} + \frac{\eta_H}{2} \left( \frac{\hat{h}_t}{\hat{h}_{t-1}} \frac{1}{\alpha \alpha^H} - 1 \right)^2 H_{t-1} \right] \right] \right\}, \end{aligned}$$

where  $\lambda_t^H$  is the price of the housing stock,  $P_t^{\hat{h}}$  is the price of new houses,  $\hat{h}_t$  denotes new houses and  $\eta_H$  is an adjustment cost parameter, and  $\alpha^H$  determines the long-run growth of newly produced

**Figure 14: Model Structure – Houses Are Produced from Intermediate Output**



houses. The law of motion for the housing stock is analogous to the one used for the capital stock, i.e. the modified adjustment cost function of Kim (2003) used by Andrieu et al. (2009) in the g3 model.

#### 4.3.2 New House-Producing Sector

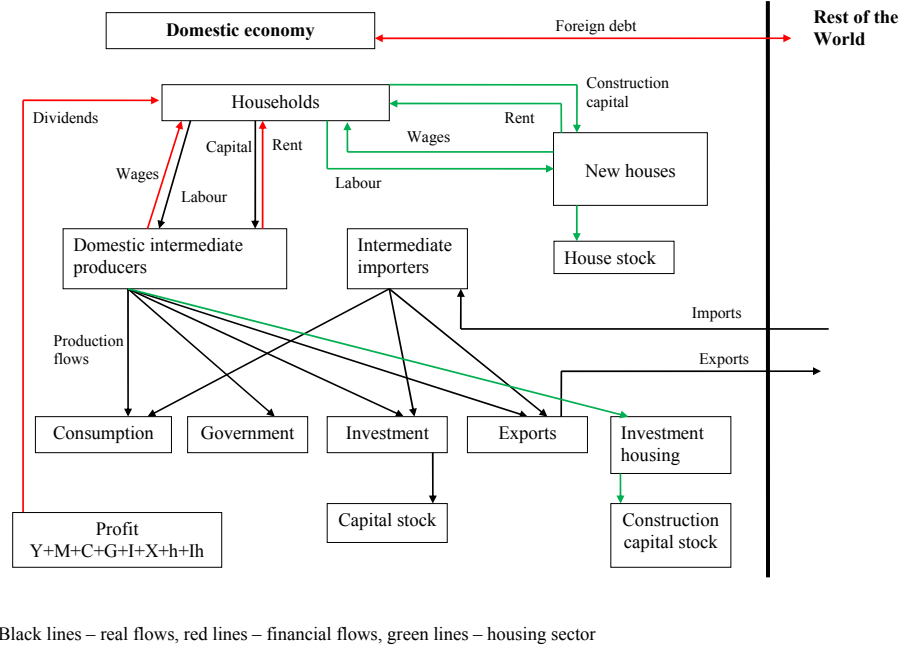
Similarly to the government goods-producing sector, monopolistically competitive firms produce new houses only from domestic intermediate goods. The production function is therefore

$$Y_t^h = \tilde{h}_t,$$

where  $Y_t^h$  denotes the part of domestic intermediate goods  $Y_t$  which is used for the production of new houses.

#### 4.4 Extension III: Houses Are Produced from Sector-Specific Inputs

In the next extension we assume that new houses are produced from sector-specific inputs. Besides providing labour and capital to domestic intermediate firms, households supply labour and rent construction capital to firms which produce new houses. Newly produced houses become a part of the housing stock, which is an argument of households' utility function. The construction capital is transformed (via a law of motion) from housing investment final goods. We assume that firms which produce housing investment final goods are monopolistically competitive and use only domestic intermediate goods as their production input. The structure of the model is shown in Figure 15.

**Figure 15: Model Structure – Houses Are Produced from Sector-Specific Inputs**

#### 4.4.1 Households

Households supply sector-specific labour and capital to new house-producing firms. They receive payments for these inputs (sector-specific wages and rent) and also dividends from both types of newly introduced firms, i.e. new house-producing firms and housing investment-producing firms. On the expenditure side of the budget constraint they purchase new houses and housing investment. Households maximise a utility function which has the form

$$\begin{aligned}
 \max_{C_t, B_t, I_t, K_t, L_t, W_t, H_t, \hat{h}_t, \mathcal{I}_t, \mathcal{K}_t, \ell_t, \mathcal{W}_t} \mathbb{E}_0 \sum_{t=0}^{\infty} \left( \prod_{\tau=0}^t \beta_{\tau} \right) & \left\{ (1-\chi) \log(C_t - \chi \bar{C}_t^F) + \frac{\phi_H \exp(\varepsilon_t^H) H_t^{1-\eta}}{1-\eta} \right. \\
 & + \phi_L a_t^L (1-L_t) + \phi_{\ell} a_t^{\ell} (1-\ell_t) - \lambda_t \left[ P_t^C C_t + P_t^I I_t + B_t + P_t^{\hat{h}} \hat{h}_t + P_t^{\mathcal{I}} \mathcal{I}_t \right. \\
 & - W_t L_t - \mathcal{W}_t \ell_t - R_{t-1} B_{t-1} - Q_t K_{t-1} - \mathcal{Q}_t \mathcal{K}_{t-1} - P_t^C T_t - \Phi_t \\
 & + \lambda_t^K \left[ K_t - K_{t-1}^{1-\delta_K} \left( \frac{I_t}{\delta_K} \right)^{\delta_K} + \frac{\eta_K}{2} \left( \frac{I_t}{I_{t-1}} \frac{1}{\alpha \alpha^I} - 1 \right)^2 K_{t-1} \right] \\
 & + \lambda_t^H \left[ H_t - H_{t-1}^{1-\delta_H} \left( \frac{\hat{h}_t}{\delta_H} \right)^{\delta_H} + \frac{\eta_H}{2} \left( \frac{\hat{h}_t}{\hat{h}_{t-1}} \frac{1}{\alpha \alpha^H} - 1 \right)^2 H_{t-1} \right] \\
 & \left. \left. + \lambda_t^{\mathcal{K}} \left[ \mathcal{K}_t - \mathcal{K}_{t-1}^{1-\delta_{\mathcal{K}}} \left( \frac{\mathcal{I}_t}{\delta_{\mathcal{K}}} \right)^{\delta_{\mathcal{K}}} + \frac{\eta_{\mathcal{K}}}{2} \left( \frac{\mathcal{I}_t}{\mathcal{I}_{t-1}} \frac{1}{\alpha \alpha^{\mathcal{I}}} - 1 \right)^2 \mathcal{K}_{t-1} \right] \right] \right\},
 \end{aligned}$$

where  $\ell_t$  denotes labour in the housing sector,  $\mathcal{W}_t$  is the nominal wage in the housing sector,  $\mathcal{I}_t$  denotes real housing investment,  $P_t^{\mathcal{I}}$  is the housing investment deflator,  $\mathcal{Q}_t \mathcal{K}_{t-1}$  is households'

income from the rented capital stock,  $\lambda_t^{\mathcal{K}}$  is the price of construction capital,  $a_t^\ell$  is a labour supply shock in the housing sector and  $\phi_\ell$  is a scaling parameter.

#### 4.4.2 Production of New Houses

A continuum of monopolistically competitive firms produce new houses by hiring labour and renting capital from households. Based on the Cobb-Douglas production technology, the cost minimisation is

$$\min_{\kappa_t, \ell_t} \mathbb{E}_0 \sum_{t=0}^{\infty} \left( \prod_{\tau=0}^t \beta_\tau \right) \left[ \mathcal{Q}_t \kappa_t + \mathcal{W}_t \ell_t + q_t^h (\bar{h}_t - a_t^h \kappa_t^{1-\gamma_\ell} (A_t \ell_t)^{\gamma_\ell}) \right],$$

where  $\mathcal{Q}$  is the rent from construction capital,  $\kappa_t \equiv \mathcal{K}_{t-1}$  is the construction capital substituted into period  $t$ ,  $q_t^h$  denotes nominal marginal costs,  $a_t^h$  is a sector-specific TFP shock and  $\gamma_\ell$  is the labour share. We assume that there is only one labour-augmenting technology in the model, i.e.  $A_t$  is the same as for domestic intermediate producers.

Firms maximise their profits subject to the downward-sloping demand curve and the Calvo-Yun setup with a full indexation scheme

$$\max_{\bar{h}_t, P_t^h} \mathbb{E}_0 \sum_{t=0}^{\infty} \left( \prod_{\tau=0}^t \beta_\tau \right) \left[ P_t^h \bar{h}_t - q_t^h \bar{h}_t \right],$$

where

$$\bar{h}_t = \left( \frac{P_t^h}{\bar{P}_t^h} \right)^{-\nu_{P^h}} \bar{h}_t.$$

#### 4.4.3 Housing Investment Goods-Producing Firms

Monopolistically competitive firms produce housing investment final goods only from domestic intermediate goods. The production function is

$$Y_t^{\mathcal{J}} = \mathcal{J}_t,$$

where  $Y_t^{\mathcal{J}}$  denotes the part of domestic intermediate goods  $Y_t$  used for the production of new houses.

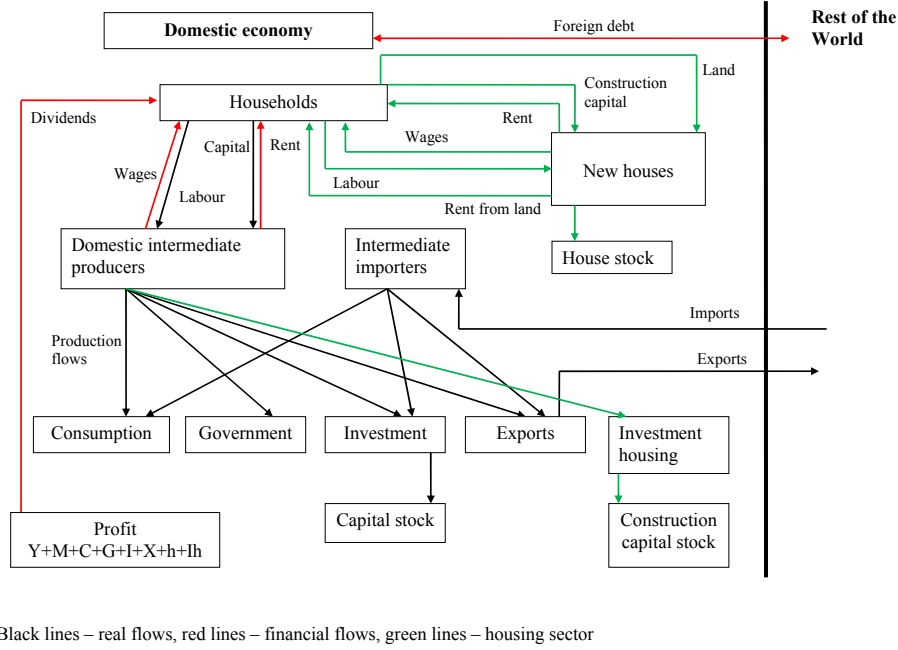
Profit maximisation is

$$\max_{\mathcal{J}_t, P_t^{\mathcal{J}}} \mathbb{E}_0 \sum_{t=0}^{\infty} \left( \prod_{\tau=0}^t \beta_\tau \frac{\lambda_t}{\lambda_0} \right) \left[ P_t^{\mathcal{J}} \mathcal{J}_t - q_t^{\mathcal{J}} \mathcal{J}_t \right],$$

where  $q_t^{\mathcal{J}}$  denotes nominal marginal costs.

### 4.5 Extension IV: Houses Are Produced from Sector-Specific Inputs and Land

As an extension of the previous version of the model, we incorporate land into the model. Households can trade in land and also rent it to new house producers, who use it as a third production input (besides labour and capital). The structure of the model is presented in Figure 16.

**Figure 16: Model Structure – Houses Are Produced from Sector-Specific Inputs and Land**

#### 4.5.1 Households

In contrast to the previous model, households supply land to new house-producing firms and receive rent. They can also trade in land. The utility maximisation is

$$\begin{aligned}
 \max_{C_t, B_t, I_t, K_t, L_t, W_t, H_t, \tilde{h}_t, \mathcal{I}_t, \mathcal{K}_t, \ell_t, \mathcal{W}_t, \mathcal{L}_t} \mathbb{E}_0 \sum_{t=0}^{\infty} \left( \prod_{\tau=0}^t \beta_{\tau} \right) & \left\{ (1-\chi) \log(C_t - \chi \bar{C}_t^F) + \frac{\phi_H \exp(\varepsilon_t^H) H_t^{1-\eta}}{1-\eta} \right. \\
 & + \phi_L a_t^L (1-L_t) + \phi_{\ell} a_t^{\ell} (1-\ell_t) - \lambda_t \left[ P_t^C C_t + P_t^I I_t + B_t + P_t^{\tilde{h}} \tilde{h}_t + P_t^{\mathcal{I}} \mathcal{I}_t + P_t^{\mathcal{L}} \mathcal{L}_t \right. \\
 & - W_t L_t - \mathcal{W}_t \ell_t - R_{t-1} B_{t-1} - Q_t K_{t-1} - \mathcal{Q}_t \mathcal{K}_{t-1} - \mathcal{Q}_t^{\mathcal{L}} \mathcal{L}_{t-1} - P_t^{\mathcal{L}} \mathcal{L}_{t-1} - P_t^C T_t - \Phi_t \\
 & + \lambda_t^K \left[ K_t - K_{t-1}^{1-\delta_K} \left( \frac{I_t}{\delta_K} \right)^{\delta_K} + \frac{\eta_K}{2} \left( \frac{I_t}{I_{t-1}} \frac{1}{\alpha \alpha^I} - 1 \right)^2 K_{t-1} \right] \\
 & + \lambda_t^H \left[ H_t - H_{t-1}^{1-\delta_H} \left( \frac{\tilde{h}_t}{\delta_H} \right)^{\delta_H} + \frac{\eta_H}{2} \left( \frac{\tilde{h}_t}{\tilde{h}_{t-1}} \frac{1}{\alpha \alpha^H} - 1 \right)^2 H_{t-1} \right] \\
 & \left. \left. + \lambda_t^{\mathcal{K}} \left[ \mathcal{K}_t - \mathcal{K}_{t-1}^{1-\delta_{\mathcal{K}}} \left( \frac{\mathcal{I}_t}{\delta_{\mathcal{K}}} \right)^{\delta_{\mathcal{K}}} + \frac{\eta_{\mathcal{K}}}{2} \left( \frac{\mathcal{I}_t}{\mathcal{I}_{t-1}} \frac{1}{\alpha \alpha^{\mathcal{I}}} - 1 \right)^2 \mathcal{K}_{t-1} \right] \right] \right\},
 \end{aligned}$$

where  $P_t^{\mathcal{L}}$  is the price of land,  $\mathcal{L}_t$  denotes land and  $\mathcal{Q}_t^{\mathcal{L}}$  is the rent from land.

#### 4.5.2 Production of New Houses

Firms use construction capital, labour and land to produce new houses. They minimise their production costs

$$\min_{\kappa_t, \ell_t, \mathcal{L}_t} \mathbb{E}_0 \sum_{t=0}^{\infty} \left( \prod_{\tau=0}^t \beta_{\tau} \frac{\lambda_t}{\lambda_0} \right) \left[ \mathcal{Q}_t \kappa_t + \mathcal{W}_t \ell_t + \mathcal{Q}_t^{\mathcal{L}} \mathcal{L}_t + q_t^{\hat{h}} (\hat{h}_t - A_t^{\hat{h}} \kappa_t^{\gamma_{\kappa}} (A_t \ell_t)^{\gamma_{\ell}} \mathcal{L}_t^{(1-\gamma_{\kappa}-\gamma_{\ell})}) \right].$$

The profit maximisation has the same form as in the previous model, except that the nominal marginal costs of the new house-production process  $q_t^{\hat{h}}$  are now a function also of the costs of renting land from households.

#### 4.6 Extension V: Non-separable Utility Function

In this framework we assume a non-separable utility function of households in consumption and ownership of houses. We choose the model in which houses are produced from intermediate output due to its medium complexity among the four housing sector extensions. The rest of the assumptions (model structure, pricing behaviour etc.) are unchanged.

##### 4.6.1 Households

Households maximise utility, which has the form

$$\begin{aligned} \max_{C_t, B_t, I_t, K_t, L_t, W_t, H_t, \hat{h}_t} E_t \sum_{t=0}^{\infty} \left( \prod_{\tau=0}^t \beta_{\tau} \right) & \left\{ (1-\chi) \log(\mathfrak{J}_t - \chi \mathfrak{J}_t^F) + \phi_L a_t^L (1-L_t) \right. \\ & - \lambda_t \left[ P_t^C C_t + P_t^I I_t + B_t + P_t^{\hat{h}} \hat{h}_t - W_t L_t - R_{t-1} B_{t-1} - Q_t K_{t-1} - P_t^C T_t - \Phi_t \right. \\ & \quad + \lambda_t^K \left[ K_t - K_{t-1}^{1-\delta_K} \left( \frac{I_t}{\delta_K} \right)^{\delta_K} + \frac{\eta_K}{2} \left( \frac{I_t}{I_{t-1}} \frac{1}{\alpha \alpha^I} - 1 \right)^2 K_{t-1} \right] \\ & \quad \left. \left. + \lambda_t^H \left[ H_t - H_{t-1}^{1-\delta_H} \left( \frac{\hat{h}_t}{\delta_H} \right)^{\delta_H} + \frac{\eta_H}{2} \left( \frac{\hat{h}_t}{\hat{h}_{t-1}} \frac{1}{\alpha \alpha^H} - 1 \right)^2 H_{t-1} \right] \right] \right\}, \end{aligned}$$

where

$$\mathfrak{J}_t \equiv \begin{cases} \left[ (1-\phi_H) C_t^{-\rho_{ns}} + \phi_H \exp(\varepsilon_t^H) \left( \frac{H_t}{A_t^H} \right)^{-\rho_{ns}} \right]^{\frac{-1}{\rho_{ns}}} & \text{if } \rho_{ns} \neq 0 \\ C_t^{1-\phi_H} \left( \exp(\varepsilon_t^H) \frac{H_t}{A_t^H} \right)^{\phi_H} & \text{if } \rho_{ns} = 0 \end{cases}.$$

The scaling of  $H_t$  in the utility function reflects the need for stationarity of the model steady state. However, it should be noted that – in addition to this pragmatic reason – the scaling used can serve as a device for modelling slowly changing preferences about the relative desirability of housing services.

The external habit formation is

$$\mathfrak{J}_t^F \equiv \begin{cases} \exp(\varepsilon_t^C) \left[ \left[ (1-\phi_H) \bar{C}_{t-1}^{-\rho_{ns}} + \phi_H \left( \frac{\bar{H}_{t-1}}{A_{t-1}^H} \right)^{-\rho_{ns}} \right]^{\frac{-1}{\rho_{ns}}} \right] & \text{if } \rho_{ns} \neq 0 \\ \exp(\varepsilon_t^C) \left[ \bar{C}_{t-1}^{1-\phi_H} \left( \frac{\bar{H}_{t-1}}{A_{t-1}^H} \right)^{\phi_H} \right] & \text{if } \rho_{ns} = 0 \end{cases}.$$

## 4.7 Calibration of Models

This section discusses the calibration of the models. Since the housing sector implementation is an extension rather than a *new model*, we first set the baseline framework parameters that are common across all the housing sector extensions. We distinguish, and calibrate successively, four groups of parameters, namely (i) the calibration of the BGP, (ii) other deep parameters defining the steady state, (iii) adjustment costs and persistence parameters, and (iv) standard deviations of structural shocks and measurement errors. After this, we proceed to calibration of the housing sector extensions.

### Balanced Growth Path

The model has a balanced growth path, along which all the model variables either are constant or grow at some growth rate. The aggregate growth is set to 3.5%, which is relevant for (real) consumption, government spending, investment and real wages. The long-run growth of exports and imports is set to 7%. The domestic inflation target is 2% in annual terms, which corresponds to the CNB's current target for MP-relevant inflation. The foreign inflation target is also 2%. The steady-state nominal appreciation rate is set to 2.4% a year.<sup>30</sup> The steady state for domestic and foreign interest rates is 3%. The long-run value of foreign GDP growth is 1.8%.

### Deep Parameters

The deep parameters are set with respect to the data and model properties. The steady state of the discount parameter  $\beta$  is set to 0.99 in annual terms. The share of labour in domestic intermediate production  $\gamma$  is 0.7. We set the capital depreciation parameter  $\delta$  to 0.015, which implies depreciation of 6% in per annum terms.<sup>31</sup> The scale parameter of hours worked in the utility function  $\phi_N$  is set to 0.34. The habit formation parameter  $\chi$  is 0.7, reflecting the inertia of consumption dynamics in the data. There are seven parameters for the elasticities of substitution among differentiated goods and labour types. Given the data uncertainties and lack of micro data analyses, they are set to 6, so the average markup is 20% in each sector. The Leontief shares for imported production components are 0.12 for consumption production ( $\omega_C$ ), 0.27 for investment production ( $\omega_I$ ) and 0.60 for export production ( $\omega_X$ ).<sup>32</sup>

### Adjustment Costs and Persistence Parameters

The calibration of adjustment costs and persistence parameters determines the business cycle properties of the model. The weight on the deviation of inflation from the target in the reaction function  $\psi$  is 2, which ensures that inflation returns to the target within the MP horizon (approx. 4–6 quarters ahead). The Calvo parameter for inflation in the consumption sector is 0.65, implying a stickiness

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<sup>30</sup> This value was set with respect to the past evolution of the Czech economy. Although the value of this parameter is currently probably rather lower, due, for example, to the ongoing convergence process, we do not change it.

<sup>31</sup> Christiano and Vigfusson (2003) estimate the depreciation rate at 0.73, which is larger than would seem plausible. They discuss this issue in greater detail.

<sup>32</sup> Note that these parameters do not correspond to the overall import intensities in the economy. For example, the import intensity of investment is set to 60%.



lasting around three quarters.<sup>33</sup> The Calvo parameter for wage-setting is 0.8, as wage stickiness is higher than price stickiness in the Czech economy.<sup>34</sup> Except for the Calvo parameter for the government goods-producing sector (0.75), the rest of the sectors are assumed to have higher flexibility. Specifically, the value for the import sector is 0.6, export sector stickiness is calibrated to 0.55 and the Calvo parameters in the investment and domestic intermediate sectors are set to 0.5. The adjustment cost parameter for investment ( $\eta_K$ ) is 0.2. The persistences of the domestic interest rate ( $\rho_R$ ) and exchange rate ( $\rho_S$ ) are set to 0.75 and 0.7 respectively. The persistence of government spending is 0.9. The persistence parameters for exogenous (technology) processes range between 0.1 and 0.7. The persistence parameters for foreign variables are 0.75 for the foreign interest rate and foreign demand and 0.3 for foreign inflation.

### **Housing Sector Parameters**

We do not need to change any deep parameters when incorporating the housing sector. For simplicity, we solve the models numerically. This implies that the values of some of the parameters may be relatively sensitive in order for the model(s) to have a solution. We tested this ‘robustness’, and the ‘boundaries’ turned out to be relatively far from our calibration for the parameters tested, even for the most complex models. Also, we do not implement any strong or contentious assumptions into the models. For example, we do not assume the presence of house prices in the reaction function of the central bank (the CB targets inflation only) and we assume the same values of housing sector parameters as for their standard counterparts.<sup>35</sup>

We thus set the housing sector parameters in line with the baseline model. Specifically, the share of labour in the production function is 0.7 and the investment adjustment cost parameter for the housing sector law of motion is also 0.2. We assume a 20% markup for monopolistically competitive firms and the same stickiness of wages and investment prices (Calvo parameters 0.8 and 0.5 respectively). The rate of depreciation is 0.0115. The Calvo parameter for prices of new houses is 0.6, implying slightly higher flexibility than in the consumption sector. In the model with land, we assume that land has a 5% share in the Cobb-Douglas function, implying a 0.25% share for capital. The housing sector parameter  $\eta$  is set to 1 as a benchmark. This value implies that the marginal utilities of consumption and housing have the same shape. We discuss the results of this and alternative assumptions in the next part of the paper.

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<sup>33</sup> There are some empirical papers which deal with nominal price rigidities. In the Czech case, Murárik (2011) uses the detailed database from the Czech Statistical Office. He finds that the average period without a price change is between 6 and 11 months for the whole consumption basket. The lower value is the result of a direct calculation, whereas the upper value stems from an implicit calculation concerning data uncertainty. He claims that the ‘true’ period probably lies near the upper bound. These values are in line with Nakamura and Steinsson (2008), who estimate a range of 8–11 months for the US economy.

<sup>34</sup> This is consistent with the empirical analyses by Babecký et al. (2008) and Druant et al. (2012) and with the setting in (Andrle et al., 2009).

<sup>35</sup> The only exception is the rate of depreciation of construction capital, which, for numerical reasons, is calibrated at a value slightly lower than the rate of depreciation of the baseline model capital stock.

## 5. Model Properties

This section presents the properties of the models and compares their performance on data. For the simulation of the model (impulse responses) and the derivation of the model moments, we used the IRIS toolbox (Beneš et al., 2014). All figures are given in the Appendix.

### 5.1 Impulse Responses

In this part we present the impulse responses of our models. We divide this subsection into three parts. First, we discuss impulse responses to ‘standard shocks’ among several models. Specifically, we compare the IRFs of the baseline model with the housing sector extensions. Second, we compare the impulse responses to housing sector shocks. Since a number of these shocks increase with the complexity of the housing sector in each model, we select the most common shocks. Specifically, we are interested in a housing preference shock, a cost-push shock to prices of new houses and a housing technology shock. And third, we solve the models for multiple parameterisations to show the sensitivity of housing sector variables.

We denote our cascade of models containing the housing sector as follows: **Baseline** is the model without the housing sector, **fS** denotes the model with an exogenous number of houses, **fY** denotes the model in which houses are produced using the domestic intermediate good, **fKL** denotes the model in which houses are produced from sector-specific labour and capital, **fKLP** denotes the version of the model with land, and finally **fYns** is the model with non-separable utility in which houses are produced using the domestic intermediate good.

#### Impulse Responses to Standard Shocks

Figure B.1 shows the reactions of the model variables to a monetary policy shock. After an interest rate increase, consumption, investment expenditure, exports, imports and nominal wages fall. The nominal exchange rate appreciates, implying additional anti-inflationary pressures in the economy via lower import prices. The MP shock implies a decrease in new house construction and in both housing sector prices (house prices and prices of newly constructed houses). The incorporation of the housing sector does not change the responses of the other model variables.<sup>36</sup> The reaction of housing sector variables is similar across the model frameworks: because the MP shock is contractionary, it also suppresses housing demand, hence lowering house prices and house production. This is a realistic feature.

Figure B.2 shows the impulse responses to a habit shock. Consumption expenditure increases. Since investment spending and exports are almost untouched, the higher consumption leads to an increase in imports. Facing inflationary pressures stemming from domestic demand, the central bank increases interest rates, although this reaction is relatively moderate as we assume a non-persistent shock. The volume of new houses decreases negligibly in more complex models due to both an increase in the interest rate and a substitution effect towards consumption. The same effects explain why house prices decrease slightly in all the models. The producer prices of new houses increase if the houses are produced from domestic intermediate goods (because the price of

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<sup>36</sup> In general, we welcome this result, as we do not regard the housing sector as a factor which *should* change the behaviour of the (model or real) economy significantly. On the other hand, we do not consider the specific situation of a pricking of a bubble (together with a deep recession) and its adverse effects on banks’ balance sheets.

domestic intermediate goods,  $\dot{dot\_Py}$ , increases as well), but decrease if houses are produced from sector-specific inputs (because of the substitution effect).

Figure B.3 presents a total factor productivity shock. Since the economy is temporarily more productive, intermediate output rises. Consumption and net exports increase, while investment expenditure falls slightly.<sup>37</sup> The monetary authority cuts the interest rate to push the lower headline inflation back to the target. The nominal exchange rate depreciates temporarily.<sup>38</sup> Because of the demand effect, house prices and the production of new houses both increase, but because of the higher productivity, the *producer prices* of new houses decline.

Figure B.4 presents the model behaviour after a cost-push shock to headline inflation. After such a shock, consumption expenditure decreases and investment expenditure temporarily increases due to substitution effects. The nominal exchange rate depreciates due to the inflation differential between the home and foreign economy (relative PPP theory). The monetary authority increases interest rates to bring inflation back to the target. House prices react to the increase in overall inflation in the economy, although their reaction is slightly smaller. The construction of new houses rises, while their prices show a hump-shaped response.

Figure B.5 presents the impulse responses to a wage-push shock. Household consumption and exports fall, while investment expenditure rises slightly due to the substitution effect. Since wage growth is not supported by higher productivity and thus creates inflationary pressures in the domestic intermediate sector which spill over into headline inflation, the monetary authority increases interest rates and hence the nominal exchange rate appreciates. House prices decrease. The size of the reaction of new house construction differs between the fY version (where it corresponds to consumption expenditure) and the fLK and fLKP models, where this sector is more isolated from the domestic intermediate sector. Moreover, the producer price of new houses initially increases in the fY version (as the intermediate good is now more expensive) but decreases slightly in the fLK and fLKP models.

Figure B.6 shows the impulse responses to a UIP shock. The depreciated nominal exchange rate implies inflationary pressures in the import intermediate sector. The central bank increases interest rates to bring inflation back to the target. Net exports increase and consumption and investment expenditures fall due to the production switch and higher import prices. The responses of new house production are negligible. House prices fall in reaction to the lower domestic demand and higher interest rates.

Figure B.7 shows the impulse responses to a foreign interest rate shock. The exchange rate depreciates due to the negative interest rate differential, and import price inflation increases. The monetary authority hikes interest rates to bring headline inflation back to the target. Net exports increase and consumption and investment expenditure fall. Similarly to a UIP shock, house prices decrease in response to the lower domestic demand and the monetary tightening. The price and volume of new houses fall with similar magnitude.

Figure B.8 presents the impulse responses to an increase in foreign prices in the foreign currency. Since there is a negative inflation differential, the exchange rate appreciates. Net exports increase

<sup>37</sup> In the closed economy version of the model, a positive TFP shock implies an increase in both consumption and investment.

<sup>38</sup> In contrast to a (permanent) labour-augmenting technology shock, a transient TFP shock implies higher supply of goods (with respect to the steady state of the economy). Given the same foreign demand, the real exchange rate must depreciate for the economy to be able to sell more exports in foreign markets.

after the shock. The central bank increases domestic interest rates slightly.<sup>39</sup> The shock has only limited effects on housing sector variables; house prices decrease (due to lower domestic demand).

Figure B.9 shows the reaction of the model variables to a foreign demand shock. Consumption, investment, net exports and nominal wages increase. Domestic intermediate inflation rises. The exchange rate appreciates and import price inflation falls. Since the anti-inflationary pressures from the imported goods sector outweigh the inflationary pressures from the domestic economy, the monetary authority lowers interest rates. House prices increase in reaction to the higher domestic demand. Both new house production and new house prices increase, although the magnitude is relative small since the shock primarily affects exports.

Figure B.10 shows the reaction of the model variables to a shock to the discount factor. Imports and consumption (through their significant import content) fall, implying negative domestic demand pressures. The monetary authority reduces interest rates to bring inflation back to the target and hence the nominal exchange rate temporarily depreciates due to the negative interest rate differential. House prices increase as households switch current consumption expenditure for housing (and investment) demand. The production of new houses rises and the (producer) price of new houses falls.

All in all, we think that the extended models produce reasonable stories and the introduction of the housing market does not destroy the conventional wisdom of New Keynesian economics.

### **Impulse Responses to Housing Sector Shocks**

Figure B.11 presents the impulse responses to a shock to households' utility from the stock of houses (a housing preference shock). After the shock, which approximates higher demand for housing, house prices increase in all the models. The production of new houses rises, but the size of this increase is much lower due to the model mechanisms (the new house production process as compared to the immediate reaction of house prices). The price of new houses also rises, but the increase is negligible. The magnitude of the reaction of the standard variables is small in all the models except for the framework with a non-separable utility function, as we do not incorporate strong assumptions such as house price (inflation) targeting or about the specification of the production process. In the extension with a non-separable utility function, since consumption is linked to the housing stock, households increase their consumption in reaction to the increase in house prices.

Figure B.12 shows the reactions of the model variables to a cost-push shock to prices of new houses. Higher prices of new houses push new house volumes (construction) downwards and marginally increase house prices. Similarly to the previous case, the reactions of other variables are negligible for practical purposes.

Figure B.13 presents the impulse responses to a housing technology shock. Since the shock improves the new house production process, the volume of new houses increases and the prices of new houses fall. Except for the fS and fYns models, the reaction of house prices is negligible. In the model with a non-separable utility function, house prices increase and so does households'

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<sup>39</sup> There are two channels with opposite effects for the domestic interest rate response. First, the higher foreign inflation implies inflationary effects and the central bank, *ceteris paribus*, increases the interest rate to prevent the economy from importing higher inflation. Second, since the nominal exchange rate appreciates, it creates, *ceteris paribus*, anti-inflationary pressures in the model.

consumption and investment expenditure. This increase in economic activity, coupled with higher nominal wages, mitigates the anti-inflationary pressures from the lower prices of new houses. Thus, the reaction of the central bank is larger in the fY model than in the same framework with a non-separable utility function.

To sum up, there are two important findings. First, incorporating the housing sector into a DSGE model need not (negatively) affect the behaviour of the model in a way that would significantly change the impulse responses of the baseline framework, provided, at least, that one does not make any strong assumptions regarding the central bank's objectives or include any additional linkages or sectors. Second, although the fY and fLK(P) models imply different model mechanisms and assumptions, their behaviour is relatively similar, allowing researchers to choose the specification they prefer. Of course, we do not aim to explicitly capture the differences between the same types of characteristics in standard sectors and their housing sector counterparts. For example, we assume the same steady-state and Calvo parameters for wages in both the standard and housing sectors. We believe that in the majority of cases, such objectives (differences) are academic issues rather than regular real-time forecasting topics (due to a wide range of uncertainties). We are thus concerned more with the calibration of key housing sector parameters (see the next part) than with model selection.

### **Impulse Responses – Comparing Parameterisations of the Utility Function**

In this subsection we show the impulse responses to multiple parameterisations of the housing curvature parameter in the utility function. In the impulse responses of the previous part, we assumed  $\eta$  calibrated to 1. In this part of the paper, we discuss various parameterisations of the utility function, especially coefficient  $\eta$ .

For the sake of brevity, we show and comment on two selected impulse responses: the impulse response to the labour-augmenting technology shock and the impulse response to the housing preference shock (see Figures B.14 and B.15). This is done for the version of the model with houses produced using the intermediate sector.

There are two main results. First, different values of  $\eta$  do not change the responses of standard variables to standard shocks. After housing sector shocks, the responses of standard variables change, but the magnitudes of these changes are negligible. Second, a different curvature of  $\eta$  implies a change in the magnitude of the reactions of housing sector variables. Thus, in line with the previous part of the paper, one can set the volatilities of housing sector variables with this parameter instead of using any strong assumptions. Preserving the impulse responses of the baseline model for standard variables is a promising feature. For models with sector-specific inputs, the results are qualitatively similar, with one caveat: the models with sector-specific inputs have stability problems for low values of  $\eta$ .

### **5.2 Forecast Error Variance Decomposition**

As an additional model diagnostic, we report the forecast error variance decomposition (FEVD) for selected models. We are mainly interested in the number of shocks that drive the main variables of interest (both the main macroeconomic variables and the variables related to the housing market). The motivation is that if the main macroeconomic variables are driven by 'standard' shocks (such as technology) and the housing variables are driven by housing sector shocks, our quest to explain the housing market via standard demand and supply mechanisms will be unsuccessful. Moreover,

it would mean that house price fluctuations are not influenced by economic cycles and other driving forces are in place. Given the conclusions in the empirical part of the paper, such a result would be unsatisfactory.

First, in Table 1, we present the FEVD for model fY under our preferred calibration. The curvature parameter  $\eta$  is calibrated to 1. In the rows,  $\dot{C}$  is real consumption growth,  $\dot{I}$  is real investment growth,  $\dot{W}$  denotes nominal wage growth,  $\dot{P}_C$  is headline inflation,  $R$  is the domestic interest rate,  $\dot{P}_H$  denotes growth of house prices,  $\dot{P}_{Hbar}$  is growth of prices of new houses and  $\dot{Hbar}$  is the production of new houses. In the columns,  $A$  denotes labour-augmenting technology shocks,  $MP$  is a monetary policy shock,  $P_C$  denotes a cost-push shock to headline inflation,  $W$  denotes wage-push shocks in the wage Phillips curve,  $R^*$  is a foreign interest rate shock,  $\beta$  denotes shocks to the discount factor,  $C$  is a habit shock,  $A^Y$  denotes TFP shocks,  $UIP$  denotes UIP shocks,  $H$  is a housing preference shock,  $A^H$  is a housing technology shock and  $P^{\bar{H}}$  is a cost-push shock in the Phillips curve of prices of new houses.

**Table 1: Forecast Error Variance Decomposition (Model fY,  $\eta = 1$ )**

	$A$	$MP$	$P_C$	$W$	$R^*$	$\beta$	$C$	$A^Y$	$UIP$	$H$	$A^H$	$P^{\bar{H}}$
$\dot{C}$	0.56	0.08	0.00	0.01	0.09	0.05	0.18	0.00	0.00	0.00	0.00	0.00
$\dot{I}$	0.75	0.00	0.00	0.00	0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$\dot{W}$	0.23	0.01	0.01	0.72	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$\dot{P}_C$	0.00	0.02	0.93	0.00	0.02	0.00	0.00	0.01	0.00	0.00	0.00	0.00
$\dot{S}$	0.02	0.17	0.00	0.07	0.45	0.00	0.00	0.02	0.18	0.00	0.00	0.00
$R$	0.02	0.80	0.04	0.01	0.09	0.00	0.00	0.02	0.00	0.00	0.00	0.00
$\dot{P}_H$	0.72	0.11	0.02	0.01	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$\dot{P}_{Hbar}$	0.00	0.01	0.01	0.04	0.01	0.00	0.00	0.05	0.00	0.00	0.29	0.57
$\dot{Hbar}$	0.74	0.02	0.01	0.03	0.02	0.00	0.00	0.01	0.00	0.00	0.15	0.01

From the table, it is clear that most housing sector variables are driven by technology, which also explains the standard macroeconomic variables. This confirms that our objective to explain house price fluctuations by standard mechanisms is successful. Moreover, we thereby avoid the tendency of some DSGE models to head towards a degenerate research programme in which new shocks are constantly added to drive newly added variables (Farmer, 2010).

Obviously, the FEVD depends on the calibration of the standard errors. To prove the robustness of our results, we report the FEVD for the calibration where we increase the standard errors of housing sector shocks by 10 and 100. The results are shown in Table 2, in which the first three rows present a tenfold increase in the standard deviations of the last three shocks ( $H$ ,  $A^H$ ,  $P^{\bar{H}}$ ) and the last three rows show the results when the magnitudes of these standard deviations are multiplied by a factor of 100. From the table, it is apparent that our conclusion still holds for house prices and new house construction (a tenfold increase). Prices of new houses are of course driven by their own cost-push shock under these circumstances.

In Table 3, we show the FEVD for model fY with multiple parameterisations of the curvature parameter  $\eta$ . The results indicate that house prices and quantities are still significantly influenced by productivity, although its influence changes to a limited extent with different values of  $\eta$ .

**Table 2: Forecast Error Variance Decomposition (Model  $fY$ ,  $\eta = 1$ , Increased Std. Dev.)**

	$A$	$MP$	$Pc$	$W$	$R^*$	$A^Y$	$H$	$A^H$	$P^h$
$\dot{dot\_Ph}$	0.72	0.11	0.02	0.01	0.11	0.00	0.00	0.00	0.00
$\dot{dot\_Phbar}$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.99
$\dot{dot\_Hbar}$	0.39	0.01	0.01	0.02	0.01	0.00	0.00	0.08	0.49
$\dot{dot\_Ph}$	0.62	0.10	0.01	0.01	0.09	0.00	0.13	0.00	0.01
$\dot{dot\_Phbar}$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1
$\dot{dot\_Hbar}$	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.99

**Table 3: Forecast Error Variance Decomposition (Model  $fY$ ,  $\eta = \{1, 0.5, 2\}$ )**

	$A$ (1 / 0.5 / 2)	$H$	$A^H$	$P^h$
$\dot{dot\_Ph}$	0.72 / 0.79 / 0.65	0.00 / 0.00 / 0.00	0.00 / 0.05 / 0.01	0.00 / 0.00 / 0.00
$\dot{dot\_Phbar}$	0.00 / 0.00 / 0.00	0.00 / 0.00 / 0.00	0.29 / 0.36 / 0.28	0.57 / 0.52 / 0.57
$\dot{dot\_Hbar}$	0.74 / 0.73 / 0.74	0.00 / 0.00 / 0.00	0.15 / 0.22 / 0.09	0.01 / 0.00 / 0.02

Finally, we report the FEVD for the model with non-separable utility for multiple parameterisations of parameter  $\rho_{ns}$ . From Table 4, there are two results. First, housing sector variables are driven by productivity with a higher share than in models with separable utility functions. Second, there are minor changes in the productivity share with respect to parameter  $\rho_{ns}$ .

**Table 4: Forecast Error Variance Decomposition (Model  $fYns$ ,  $\rho_{ns} = \{1, 0.5, 10\}$ )**

	$A$ (1 / 0.5 / 10)	$H$	$A^H$	$P^h$
$\dot{dot\_Ph}$	0.80 / 0.78 / 0.80	0.00 / 0.00 / 0.00	0.02 / 0.01 / 0.13	0.00 / 0.00 / 0.00
$\dot{dot\_Phbar}$	0.01 / 0.01 / 0.01	0.00 / 0.00 / 0.00	0.27 / 0.27 / 0.27	0.58 / 0.58 / 0.58
$\dot{dot\_Hbar}$	0.77 / 0.76 / 0.76	0.00 / 0.00 / 0.00	0.17 / 0.16 / 0.21	0.00 / 0.01 / 0.00

### 5.3 Moments

In this subsection we compare the second moments between the data and our housing sector models.

Figure B.16 shows the correlation of house prices with consumption growth (C), investment growth (I), MP-relevant inflation (Pc), the policy rate (R), exchange rate change (S) and new houses (H) both in the Czech data and in our models. The green sign denotes data. The red sign denotes the point estimate based on the estimated VAR and the shadow bars denote the bootstrapped estimates of this correlation. The other signs denote the correlations implied by our baseline calibration of the model. Our model roughly corresponds to the bootstrapped confidence intervals for the correlation of house prices with consumption and investment. The model-implied correlations are rather higher than the point estimates, but given the contamination of Czech house price data (discussed in Sec-

tion 3), we do not see this as a problem. The model-implied correlations with consumer inflation are rather lower than the point estimate, but well within the confidence intervals. We match the correlations of house prices and exchange rate changes, and the model-implied correlations between the housing stock and house prices are higher in the models than in the data. Again, however, this is not necessarily a vice given the contamination of Czech housing data by non-fundamental factors.

Figure B.17 shows the correlation of new houses with aggregates. Here, our models imply rather higher correlations between houses and macroeconomic aggregates than in the data. This can be partly solved by increasing the value of  $\eta$ , as shown in Figure B.18.<sup>40</sup> Nevertheless, we are now unsure whether this would really be a plausible thing to do: our models imply higher comovements among the variables than what is observed in the Czech data, but this may only reflect the pre-2005 sample and it is not completely unrealistic to expect the comovement to increase to what is observed in advanced economies.

## 6. Conclusion

In this paper, we make two contributions to the understanding of housing market dynamics and their relationship with the macroeconomy.

First, we analyse housing market data for a large set of advanced countries and place the dynamics of the Czech housing market in this context. We show that in most advanced countries, housing market variables (prices, quantities, labour inputs) are cyclical and that in the pre-2005 period this was not always the case for the Czech economy. However, since 2005, it seems that the alignment of the housing market with the business cycle has increased in the Czech Republic as well.

Second, we present a cascade of DSGE models which incorporate the housing market. We analyse their impulse responses and show that the introduction of the housing market does not destroy the conventional wisdom of New Keynesian economics, even if the housing market extension is rather complex. We confront the model-based moments implied by the models with data and the results are not unsatisfactory. We achieve this without introducing collateral constraints or other exotic features, using just standard demand and supply mechanisms. We conclude that to incorporate the housing market into DSGE models, the standard mechanisms are sufficient. We also provide a limited sensitivity analysis with respect to the parameterisation of the utility function and discuss its impacts on the model's properties.

In the future, the research could be extended along several dimensions. Especially, we are considering introducing non-fundamental movements in house prices (aka bubbles) to be able to filter out non-fundamental episodes in the Czech housing market (such as the surge in house prices prior to EU entry). However, this is left for future research.

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<sup>40</sup> This would also be the case for the correlations of aggregates with house prices: higher values of  $\eta$  would bring them closer towards the data.



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## Appendix A: Model Equations

In this section we present the model equations. We focus mainly on the first-order conditions of the optimisation problems described above. On the other hand, we do not explicitly describe the definitions, identities or AR processes. Also, since the production functions and laws of motion are presented in the optimisation problems in Section 4, we do not repeat them in this section, although they are a necessary part of the model codes.

### A.1 Baseline Model

#### Households

The first-order conditions of households with respect to consumption, government bonds, investment and the capital stock are

$$\frac{1-\chi}{C_t - \chi \bar{C}_{t-1}^F} = \lambda_t P_t^C, \quad (\text{A.1})$$

$$\lambda_t = \beta_t \lambda_{t+1} R_t, \quad (\text{A.2})$$

$$\begin{aligned} P_t^I = & \lambda_t^K \left( \frac{\delta_K K_{t-1}}{I_t} \right)^{1-\delta_K} - \eta_K \lambda_t^K \frac{K_{t-1}}{I_{t-1}} \left( \frac{I_t}{I_{t-1}} \frac{1}{\alpha \alpha^I} - 1 \right) \frac{1}{\alpha \alpha^I} \\ & + \beta_t \eta_K \frac{\lambda_{t+1}}{\lambda_t} \lambda_{t+1}^K \frac{K_t}{I_t} \frac{I_{t+1}}{I_t} \left( \frac{I_{t+1}}{I_t} \frac{1}{\alpha \alpha^I} - 1 \right) \frac{1}{\alpha \alpha^I}, \end{aligned} \quad (\text{A.3})$$

$$\lambda_t^K = \beta_t \frac{\lambda_{t+1}}{\lambda_t} \left[ Q_{t+1} + (1 - \delta_K) \lambda_{t+1}^K \left( \frac{I_{t+1}}{\delta_K K_t} \right)^{\delta_K} - \frac{\eta_K}{2} \lambda_{t+1}^K \left( \frac{I_{t+1}}{I_t} \frac{1}{\alpha \alpha^I} - 1 \right)^2 \right]. \quad (\text{A.4})$$

Assuming the Calvo-Yun setup with a full indexation scheme, the first-order condition with respect to labour and wages is<sup>41</sup>

$$\log \left( \frac{\dot{W}_t}{\dot{W}_{t-1}} \right) = \beta_t \log \left( \frac{\dot{W}_{t+1}}{\dot{W}_t} \right) + \frac{(1 - \beta_t \Xi_w)(1 - \Xi_w)}{\Xi_w} \log \left( \frac{\phi_L a_t^L}{\lambda_t W_t} \frac{v_w}{v_w - 1} \right) + \varepsilon_t^W. \quad (\text{A.5})$$

In the model we assume persistence (via an AR process) of the discount factor  $\beta_t$ <sup>42</sup> and labour supply shocks  $a_t^L$ .

<sup>41</sup> In the first version of the model, we used Rotemberg's (Rotemberg, 1982a,b) setup, which implies an equation of the form

$$\log \left( \frac{\dot{W}_t}{\dot{W}_{t-1}} \right) = \beta_t \log \left( \frac{\dot{W}_{t+1}}{\dot{W}_t} \right) + \frac{v_w}{\xi_w} \left( \frac{\phi_L a_t^L}{\lambda_t W_t} - \frac{v_w - 1}{v_w} \right) + \varepsilon_t^W.$$

The behaviour of the model does not differ much.

<sup>42</sup> The discount factor each time is scaled by  $\beta_0$ , i.e.  $\frac{1}{\beta_0} [\beta_0 U(C_0, L_0) + \beta_0 \beta_1 U(C_1, L_1) + \dots]$ .

### Domestic Intermediate Producers

The first-order conditions with respect to capital and labour are

$$Q_t k_t = (1 - \gamma_L) q_t^Y Y_t, \quad (\text{A.6})$$

$$W_t L_t = \gamma_L q_t^Y Y_t. \quad (\text{A.7})$$

Substituting  $k_t$  and  $L_t$  from the FOC into the production function implies an equation for nominal marginal costs as a function of the weighted prices of both inputs, i.e.

$$q_t^Y = \frac{1}{a_t^Y} \frac{[Q_t]^{(1-\gamma_L)} [W_t]^{\gamma_L}}{(1-\gamma_L)^{\gamma_L} (\gamma_L)^{\gamma_L}}.$$

The Phillips curve is

$$\log \left( \frac{\dot{P}_t^Y}{\dot{P}_{t-1}^Y} \right) = \beta_t \log \left( \frac{\dot{P}_{t+1}^Y}{\dot{P}_t^Y} \right) + \frac{(1 - \beta_t \Xi_{PY})(1 - \Xi_{PY})}{\Xi_{PY}} \log \left( \frac{q_t^Y}{P_t^Y} \frac{v_{PY}}{v_{PY} - 1} \right) + \varepsilon_t^{PY}. \quad (\text{A.8})$$

Also, we assume persistence of the TFP shocks  $a_t^Y$ .

### Intermediate Importers

The Phillips curve is

$$\log \left( \frac{\dot{P}_t^M}{\dot{P}_{t-1}^M} \right) = \beta_t \log \left( \frac{\dot{P}_{t+1}^M}{\dot{P}_t^M} \right) + \frac{(1 - \beta_t \Xi_{PM})(1 - \Xi_{PM})}{\Xi_{PM}} \log \left( \frac{P_t^*}{P_t^M} \frac{v_{PM}}{v_{PM} - 1} \right) + \varepsilon_t^{PM}, \quad (\text{A.9})$$

where  $P_t^M$  is the price of imports in the domestic currency and  $P_t^*$  is the price of foreign goods in the domestic currency (nominal marginal costs), which is defined as

$$P_t^* = S_t \tilde{P}_t^*,$$

where  $\tilde{P}_t^*$  is the price of foreign goods in the foreign currency and  $S_t$  is the nominal exchange rate.

### Final-Goods Producing Firms

Assuming the Leontief production function, the first-order conditions in the consumption sector are

$$Y_t^C = (1 - \omega_C) C_t \quad (\text{A.10})$$

and

$$(M_t^C / A_t^X) = \omega_C C_t. \quad (\text{A.11})$$

The implied nominal marginal (and average) costs are

$$q_t^C = (1 - \omega_C)P_t^Y + \omega_C P_t^M A_t^X. \quad (\text{A.12})$$

The Phillips curve in the consumption goods-producing sector is

$$\log \left( \frac{\dot{P}_t^C}{\dot{P}_{t-1}^C} \right) = \beta_t \log \left( \frac{\dot{P}_{t+1}^C}{\dot{P}_t^C} \right) + \frac{(1 - \beta_t \Xi_{PC})(1 - \Xi_{PC})}{\Xi_{PC}} \log \left( \frac{q_t^C}{P_t^C} \frac{v_{PC}}{v_{PC} - 1} \right) + \varepsilon_t^{PC}. \quad (\text{A.13})$$

The equations for the investment and export goods-producing sectors are analogous, except that export prices are sticky in the foreign currency due to the local currency pricing assumption.

Final government goods are produced from domestic intermediate goods

$$G_t = Y_t^G. \quad (\text{A.14})$$

The Phillips curve in the final government goods-producing sector is

$$\log \left( \frac{\dot{P}_t^G}{\dot{P}_{t-1}^G} \right) = \beta_t \log \left( \frac{\dot{P}_{t+1}^G}{\dot{P}_t^G} \right) + \frac{(1 - \beta_t \Xi_{PG})(1 - \Xi_{PG})}{\Xi_{PG}} \log \left( \frac{q_t^G}{P_t^G} \frac{v_{PG}}{v_{PG} - 1} \right) + \varepsilon_t^{PG}, \quad (\text{A.15})$$

where nominal marginal costs are

$$q_t^G = P_t^Y. \quad (\text{A.16})$$

## Forex Dealers

Substituting the Euler equation into the FOC of forex dealers implies a debt-elastic premium version of the uncovered interest parity

$$\frac{S_{t+1}}{S_t} R_t^* = R_t (1 + \zeta \mathfrak{I}_t^{uip} B_t^*), \quad (\text{A.17})$$

where the domestic interest rate increases with the amount of foreign debt (Schmitt-Grohé and Uribe, 2003). For better model properties, spreading of  $\dot{S}$  over time is incorporated. The debt-elastic premium is persistent in time.

## Monetary Policy

$$\log R_t = \rho_R \log R_{t-1} + (1 - \rho_R) \left[ \log R + \psi \log \left( \frac{\dot{P}_{t+4}^{yy}}{\dot{P}_t^{yy}} \right) \right] + \varepsilon_t^{mp}. \quad (\text{A.18})$$

## Fiscal Policy

$$\log \left( \frac{P_t^G G_t}{P_t^C C_t} \right) = \rho_G \log \left( \frac{P_{t-1}^G G_{t-1}}{P_{t-1}^C C_{t-1}} \right) + (1 - \rho_G) \log \left( \frac{P^G G}{P^C C} \right) + \varepsilon_t^G. \quad (\text{A.19})$$

## Rest of the World

The downward-sloping demand curve for domestic exports is

$$X_t = \left( \frac{P_t^X}{P_t^*} \right)^{-\theta} N_t^*. \quad (\text{A.20})$$

Foreign variables (the foreign interest rate, foreign demand and foreign inflation) evolve according to

$$\log R_t^* = \rho_{R^*} \log R_{t-1}^* + (1 - \rho_{R^*}) \log R^* + \varepsilon_t^{R^*}, \quad (\text{A.21})$$

$$\log N_t^* = \rho_{N^*} \log N_{t-1}^* + (1 - \rho_{N^*}) \log N^* + \varepsilon_t^{N^*}, \quad (\text{A.22})$$

$$\log \hat{P}_t^* = \rho_{P^*} \log \hat{P}_{t-1}^* + (1 - \rho_{P^*}) \log \hat{P}^* + \varepsilon_t^{P^*}. \quad (\text{A.23})$$

## Balanced Growth Path

Similarly to Andrieu et al. (2009), we assume a balanced growth path where all variables are either constant or grow at a constant pace. The implied (due to the Cobb-Douglas production function) relationship is

$$\dot{Z}_t = \dot{A}_t (\dot{A}_t^I)^{\frac{1-\gamma}{\gamma}}, \quad (\text{A.24})$$

where aggregate growth  $\dot{Z}_t$  is implied by labour-augmenting technology growth  $\dot{A}$  and growth of investment-specific technology  $\dot{A}_t^I$ , which evolve according to AR processes.

## National Accounting

The market-clearing equations for domestic and imported intermediate goods are

$$Y_t = Y_t^C + Y_t^G + Y_t^I + Y_t^X \quad (\text{A.25})$$

and

$$M_t = M_t^C + M_t^I + M_t^X, \quad (\text{A.26})$$

where both domestic and imported goods are used for the production of consumption, investment and export final goods. Government final goods are produced from domestic intermediate goods only.

The budget constraints of households and government are

$$P_t^C C_t + P_t^I I_t + B_t = W_t L_t + R_{t-1} B_{t-1} + Q_t K_{t-1} + P_t^C F_t + \Phi_t \quad (\text{A.27})$$

and

$$R_{t-1} B_{t-1} + P_t^G G_t + P_t^C F_t = B_t + S_t \frac{\zeta_B}{2} \mathfrak{S}_t^{uip} (B_t^*)^2. \quad (\text{A.28})$$

Households' dividends are

$$\Phi_t = \Phi_t^Y + \Phi_t^M + \Phi_t^C + \Phi_t^G + \Phi_t^I + \Phi_t^X + \Phi_t^F, \quad (\text{A.29})$$

where

$$\begin{aligned} \Phi_t^Y &= P_t^Y Y_t - W_t L_t - Q_t k_t, \\ \Phi_t^M &= P_t^M M_t - M_t P_t^*, \\ \Phi_t^C &= P_t^C C_t - P_t^Y Y_t^C - P_t^M M_t^C, \\ \Phi_t^G &= P_t^G G_t - P_t^Y Y_t^G, \\ \Phi_t^I &= P_t^I I_t - P_t^M M_t^I, \\ \Phi_t^X &= P_t^X X_t - P_t^Y Y_t^X - P_t^M M_t^X, \\ \Phi_t^F &= S_t B_{t-1}^* i_{t-1}^* - S_t B_t^* - S_t \frac{\zeta_B}{2} \mathfrak{S}_t^{uip} (B_t^*)^2. \end{aligned}$$

The previous equations imply

$$S_t B_t^* = S_t B_{t-1}^* R_{t-1}^* + P_t^X X_t - P_t^* M_t.$$

Substituting for foreign bonds in the domestic currency  $B_t^{*,dc} = S_t B_t^*$  results in

$$B_t^{*,dc} = \dot{S}_t B_{t-1}^{*,dc} R_{t-1}^* + P_t^X X_t - P_t^* M_t.$$

Relating net foreign assets to the volume of nominal exports implies

$$\mathcal{B}_t = \dot{S}_t \mathcal{B}_{t-1} R_{t-1}^* \frac{P_{t-1}^X X_{t-1}}{P_t^X X_t} + 1 - \frac{P_t^* M_t}{P_t^X X_t}, \quad (\text{A.30})$$

where

$$\mathcal{B}_t \equiv \frac{B_t^{*,dc}}{P_t^X X_t}.$$



## A.2 Extension I: Houses Fall from the Sky

The first-order condition with respect to the stock of houses is

$$\lambda_t \lambda_t^H = \phi_H H_t^{-\eta} + \beta_t \lambda_{t+1} \lambda_{t+1}^H, \quad (\text{A.31})$$

where we assume an autoregressive process for the (stationarised) housing stock

$$\log H_t = \rho_H \log H_{t-1} + (1 - \rho_H) \log H + \varepsilon_t^H. \quad (\text{A.32})$$

Also, we assume that the stock of houses and the price of houses grow by

$$\dot{H}_t = (H_t/H_{t-1})(\dot{Z}_t \dot{A}_t^H)^{\frac{1}{\eta}} \quad (\text{A.33})$$

and

$$\dot{\lambda}_t^H = (\lambda_t^H/\lambda_{t-1}^H) \dot{P}_t^Y/\dot{A}_t^H, \quad (\text{A.34})$$

where  $A_t^H$  is a sector-wide technology compatible with the model's balanced growth path. Also, we assume it is persistent over time via an AR process.

## A.3 Extension II: Houses Are Produced from Intermediate Output

Apart from the equations in the baseline model, the first-order conditions of the household sector with respect to the stock of houses  $H_t$  and new houses  $\hat{h}_t$  are

$$\lambda_t \lambda_t^H = \phi_H \exp(\varepsilon_t^H) H_t^{-\eta} + \beta_t \lambda_{t+1} \lambda_{t+1}^H \left[ (1 - \delta_H) \left( \frac{\hat{h}_{t+1}}{\delta_H H_t} \right)^{\delta_H} - \frac{\eta_H}{2} \left( \frac{\hat{h}_{t+1}}{\hat{h}_t} \frac{1}{\alpha \alpha^H} - 1 \right)^2 \right], \quad (\text{A.35})$$

$$\begin{aligned} P_t^{\hat{h}} = & \lambda_t^H \left( \frac{\delta_H H_{t-1}}{\hat{h}_t} \right)^{1-\delta_H} - \eta_H \lambda_t^H \frac{H_{t-1}}{\hat{h}_{t-1}} \left( \frac{\hat{h}_t}{\hat{h}_{t-1}} \frac{1}{\alpha \alpha^H} - 1 \right) \frac{1}{\alpha \alpha^H} \\ & + \beta_t \eta_H \frac{\lambda_{t+1}}{\lambda_t} \lambda_{t+1}^H \frac{H_t}{\hat{h}_t} \frac{\hat{h}_{t+1}}{\hat{h}_t} \left( \frac{\hat{h}_{t+1}}{\hat{h}_t} \frac{1}{\alpha \alpha^H} - 1 \right) \frac{1}{\alpha \alpha^H}. \end{aligned} \quad (\text{A.36})$$

The Phillips curve for the new house-producing sector is

$$\log \left( \frac{\dot{P}_t^{\hat{h}}}{\dot{P}_{t-1}^{\hat{h}}} \right) = \beta_t \log \left( \frac{\dot{P}_{t+1}^{\hat{h}}}{\dot{P}_t^{\hat{h}}} \right) + \frac{(1 - \beta_t \Xi_{P^{\hat{h}}})(1 - \Xi_{P^{\hat{h}}})}{\Xi_{P^{\hat{h}}}} \log \left( \frac{P_t^Y}{P_t^{\hat{h}}} \frac{v_{P^{\hat{h}}}}{v_{P^{\hat{h}}} - 1} \right) + \varepsilon_t^{P^{\hat{h}}}. \quad (\text{A.37})$$

The market-clearing condition for domestic intermediate goods is modified to incorporate the production of new houses

$$Y_t = Y_t^C + Y_t^G + Y_t^I + Y_t^X + Y_t^{\hat{h}}. \quad (\text{A.38})$$

The dividends from the new house sector are

$$\Phi_t^{\hat{h}} = P_t^{\hat{h}} \hat{h}_t - P_t^Y Y_t^{\hat{h}}, \quad (\text{A.39})$$

which does not imply any change in the NFA equation, since  $P_t^{\bar{h}} \bar{h}_t$  are purchased by households.

The assumption of a balanced growth path with respect to  $\dot{H}_t$  and  $\dot{\lambda}_t^H$  does not change (equations A.33 and A.34). The growth rates and prices of new houses are

$$\dot{\bar{h}}_t = (\bar{h}_t / \bar{h}_{t-1}) (\dot{Z}_t \dot{A}_t^H)^{\frac{1}{\eta}} \quad (\text{A.40})$$

and

$$\dot{P}_t^{\bar{h}} = (P_t^{\bar{h}} / P_{t-1}^{\bar{h}}) \dot{P}_t^Y / \dot{A}_t^H. \quad (\text{A.41})$$

#### A.4 Extension III: Houses Are Produced from Sector-Specific Inputs

With respect to the housing sector, the model contains the first-order equations described earlier (A.35 and A.36). The first-order conditions of households with respect to investment in houses, capital for house construction and labour and wages in the housing sector (the wage Phillips curve) are

$$\begin{aligned} P_t^{\mathcal{J}} = & \lambda_t^{\mathcal{K}} \left( \frac{\delta_{\mathcal{K}} \mathcal{K}_{t-1}}{\mathcal{J}_t} \right)^{1-\delta_{\mathcal{K}}} - \eta_{\mathcal{K}} \lambda_t^{\mathcal{K}} \frac{\mathcal{K}_{t-1}}{\mathcal{J}_{t-1}} \left( \frac{\mathcal{J}_t}{\mathcal{J}_{t-1}} \frac{1}{\alpha \alpha^{\mathcal{J}}} - 1 \right) \frac{1}{\alpha \alpha^{\mathcal{J}}} \\ & + \beta_t \eta_{\mathcal{K}} \frac{\lambda_{t+1}}{\lambda_t} \lambda_{t+1}^{\mathcal{K}} \frac{\mathcal{K}_t}{\mathcal{J}_t} \frac{\mathcal{J}_{t+1}}{\mathcal{J}_t} \left( \frac{\mathcal{J}_{t+1}}{\mathcal{J}_t} \frac{1}{\alpha \alpha^{\mathcal{J}}} - 1 \right) \frac{1}{\alpha \alpha^{\mathcal{J}}}, \end{aligned} \quad (\text{A.42})$$

$$\lambda_t^{\mathcal{K}} = \beta_t \frac{\lambda_{t+1}}{\lambda_t} \left[ \mathcal{Q}_{t+1} + (1 - \delta_{\mathcal{K}}) \lambda_{t+1}^{\mathcal{K}} \left( \frac{\mathcal{J}_{t+1}}{\delta_{\mathcal{K}} \mathcal{K}_t} \right)^{\delta_{\mathcal{K}}} - \frac{\eta_{\mathcal{K}}}{2} \lambda_{t+1}^{\mathcal{K}} \left( \frac{\mathcal{J}_{t+1}}{\mathcal{J}_t} \frac{1}{\alpha \alpha^{\mathcal{J}}} - 1 \right)^2 \right] \quad (\text{A.43})$$

and

$$\log \left( \frac{\mathcal{W}_t}{\mathcal{W}_{t-1}} \right) = \beta_t \log \left( \frac{\mathcal{W}_{t+1}}{\mathcal{W}_t} \right) + \frac{(1 - \beta_t \Xi_{\mathcal{W}})(1 - \Xi_{\mathcal{W}})}{\Xi_{\mathcal{W}}} \log \left( \frac{\phi_{\ell} a_t^{\ell}}{\lambda_t \mathcal{W}_t} \frac{v_{\mathcal{W}}}{v_{\mathcal{W}} - 1} \right) + \varepsilon_t^{\mathcal{W}}. \quad (\text{A.44})$$

#### Production of New Houses

The first-order conditions with respect to both inputs are

$$\mathcal{Q}_t \kappa_t = (1 - \gamma_{\ell}) q_t^{\bar{h}} \bar{h}_t \quad (\text{A.45})$$

and

$$\mathcal{W}_t \ell_t = \gamma_{\ell} q_t^{\bar{h}} \bar{h}_t. \quad (\text{A.46})$$

The Phillips curve is

$$\log \left( \frac{\dot{P}_t^{\bar{h}}}{\dot{P}_{t-1}^{\bar{h}}} \right) = \beta_t \log \left( \frac{\dot{P}_{t+1}^{\bar{h}}}{\dot{P}_t^{\bar{h}}} \right) + \frac{(1 - \beta_t \Xi_{P^{\bar{h}}})(1 - \Xi_{P^{\bar{h}}})}{\Xi_{P^{\bar{h}}}} \log \left( \frac{q_t^{\bar{h}}}{P_t^{\bar{h}}} \frac{v_{P^{\bar{h}}}}{v_{P^{\bar{h}}} - 1} \right) + \varepsilon_t^{P^{\bar{h}}}. \quad (\text{A.47})$$

## Housing Investment

The Phillips curve is

$$\log \left( \frac{\dot{P}_t^{\mathcal{J}}}{\dot{P}_{t-1}^{\mathcal{J}}} \right) = \beta_t \log \left( \frac{\dot{P}_{t+1}^{\mathcal{J}}}{\dot{P}_t^{\mathcal{J}}} \right) + \frac{(1 - \beta_t \Xi_{P^{\mathcal{J}}})(1 - \Xi_{P^{\mathcal{J}}})}{\Xi_{P^{\mathcal{J}}}} \log \left( \frac{P_t^Y}{P_t^{\mathcal{J}}} \frac{v_{P^{\mathcal{J}}}}{v_{P^{\mathcal{J}}} - 1} \right) + \varepsilon_t^{P^{\mathcal{J}}}, \quad (\text{A.48})$$

where nominal marginal costs are  $q_t^{\mathcal{J}} = P_t^Y$ .

## Balanced Growth Path

Since we allow for separate investment-specific technologies in both final investment goods-producing sectors, the Cobb-Douglas technology implies an equation for investment-specific technology in the housing investment sector which has the form

$$(\dot{Z}_t \dot{A}_t^H)^{\frac{1}{\eta_H}} = (\dot{Z}_t \dot{A}_t^{\mathcal{J}})^{1-\gamma_\ell} (\dot{A}_t)^{\gamma_\ell},$$

which becomes

$$\dot{A}_t^{\mathcal{J}} = \frac{(\dot{Z}_t)^{\frac{1}{\eta_H} - 1 + \gamma_\ell} (\dot{A}_t^H)^{\frac{1}{\eta_H}}}{(\dot{A}_t)^{\frac{\gamma_\ell}{1-\gamma_\ell}}}. \quad (\text{A.49})$$

Similarly to the investment sector, the growth rates of housing investment and house prices along the balanced growth path are

$$\dot{\mathcal{J}}_t = (\mathcal{J}_t / \mathcal{J}_{t-1}) (\dot{Z}_t \dot{A}_t^{\mathcal{J}}) \quad (\text{A.50})$$

and

$$\dot{P}_t^{\mathcal{J}} = (P_t^{\mathcal{J}} / P_{t-1}^{\mathcal{J}}) \dot{P}_t^Y / \dot{A}_t^{\mathcal{J}}. \quad (\text{A.51})$$

## National Accounting

The market-clearing condition for domestic intermediate goods is

$$Y_t = Y_t^C + Y_t^G + Y_t^I + Y_t^X + Y_t^{\mathcal{J}} \quad (\text{A.52})$$

and the dividends are

$$\Phi_t^{\mathcal{J}} = P_t^{\mathcal{J}} \mathcal{J}_t - P_t^Y Y_t^{\mathcal{J}}. \quad (\text{A.53})$$

### A.5 Extension IV: Houses Are Produced from Sector-Specific Inputs and Land

With respect to the housing sector, the model contains equations (A.35), (A.36), (A.42), (A.43), (A.44), (A.47), (A.48) and (A.52).

#### Households

The first-order condition with respect to land is

$$P_t^{\mathcal{L}} = \left( \beta_t \frac{\lambda_{t+1}}{\lambda_t} \right) (\mathcal{Q}_{t+1}^{\mathcal{L}} + P_{t+1}^{\mathcal{L}}), \quad (\text{A.54})$$

where we assume stationary (constant) land which evolves temporarily according to an AR process

$$\log \mathcal{L}_t = \rho_{\mathcal{L}} \log \mathcal{L}_{t-1} + (1 - \rho_{\mathcal{L}}) \log \mathcal{L} + \varepsilon_t^{\mathcal{L}}. \quad (\text{A.55})$$

The growth of land prices along the balanced growth path is

$$\dot{P}_t^{\mathcal{L}} = (P_t^{\mathcal{L}} / P_{t-1}^{\mathcal{L}}) \dot{Z}_t \dot{P}_t^Y. \quad (\text{A.56})$$

#### Production of New Houses

The first-order conditions with respect to construction capital, labour and land are

$$\mathcal{Q}_t \kappa_t = \gamma_{\kappa} q_t^{\hat{h}} \hat{h}_t, \quad (\text{A.57})$$

$$\mathcal{W}_t \ell_t = \gamma_{\ell} q_t^{\hat{h}} \hat{h}_t, \quad (\text{A.58})$$

$$\mathcal{Q}_t^{\mathcal{L}} \mathcal{L}_t = (1 - \gamma_{\kappa} - \gamma_{\ell}) q_t^{\hat{h}} \hat{h}_t. \quad (\text{A.59})$$

#### Balanced Growth Path

The relationship among technologies implies

$$\begin{aligned} \hat{h}_t = A_t^{\hat{h}} \kappa_t^{\gamma_{\kappa}} (A_t^H \ell_t)^{\gamma_{\ell}} \mathcal{L}^{(1-\gamma_{\kappa}-\gamma_{\ell})} &\Rightarrow (\dot{Z}_t \dot{A}_t^H)^{\frac{1}{\eta_H}} = (\dot{Z}_t \dot{A}_t^{\mathcal{L}})^{\gamma_{\kappa}} (\dot{A}_t^H)^{\gamma_{\ell}} \frac{1}{(\dot{A}_t^{\ell})^{\gamma_{\ell}}} \Rightarrow \\ \dot{A}_t^{\mathcal{L}} &= (\dot{Z}_t)^{\frac{\frac{1}{\eta_H}-\gamma_{\kappa}}{\gamma_{\kappa}}} (\dot{A}_t^H)^{\frac{\frac{1}{\eta_H}-\gamma_{\ell}}{\gamma_{\kappa}}} (\dot{A}_t^{\ell})^{\frac{\gamma_{\ell}}{\gamma_{\kappa}}}. \end{aligned} \quad (\text{A.60})$$

### A.6 Extension V: Non-separable Utility Function

The first-order conditions with respect to consumption and the stock of houses are

$$\lambda_t P_t^C = \frac{(1-\chi)(1-\phi_H)}{\mathfrak{I}_t - \chi \mathfrak{I}_t^F} \left( \frac{\mathfrak{I}_t}{C_t} \right)^{1+\rho_{ns}} \quad (\text{A.61})$$

and

$$\begin{aligned} \lambda_t \lambda_t^H &= \frac{(1-\chi)\phi_H \exp(\varepsilon_t^H)}{\mathfrak{I}_t - \chi \mathfrak{I}_t^F} \left[ \frac{\mathfrak{I}_t A_t^H}{H_t} \right]^{1+\rho_{ns}} \frac{1}{A_t^H} \\ &+ \beta_t \lambda_{t+1} \lambda_{t+1}^H (1-\delta_H) \left( \frac{h_{t+1}}{\delta_H H_t} \right)^{\delta_H} - \beta_t \lambda_{t+1} \lambda_{t+1}^H \frac{\eta_H}{2} \left( \frac{h_t}{h_{t-1}} \frac{1}{\alpha \alpha^H} - 1 \right)^2. \end{aligned} \quad (\text{A.62})$$

## Appendix B: Model Properties

*Figure B.1: Monetary Policy Shock*

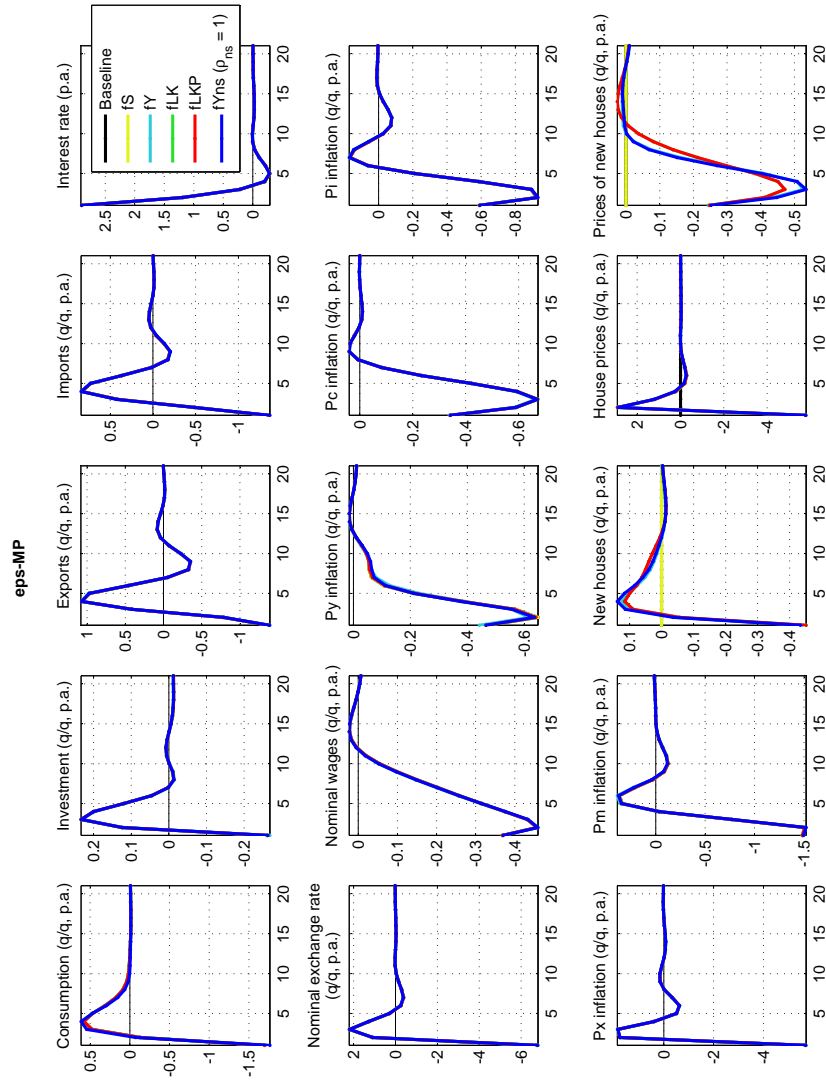


Figure B.2: Habit Shock

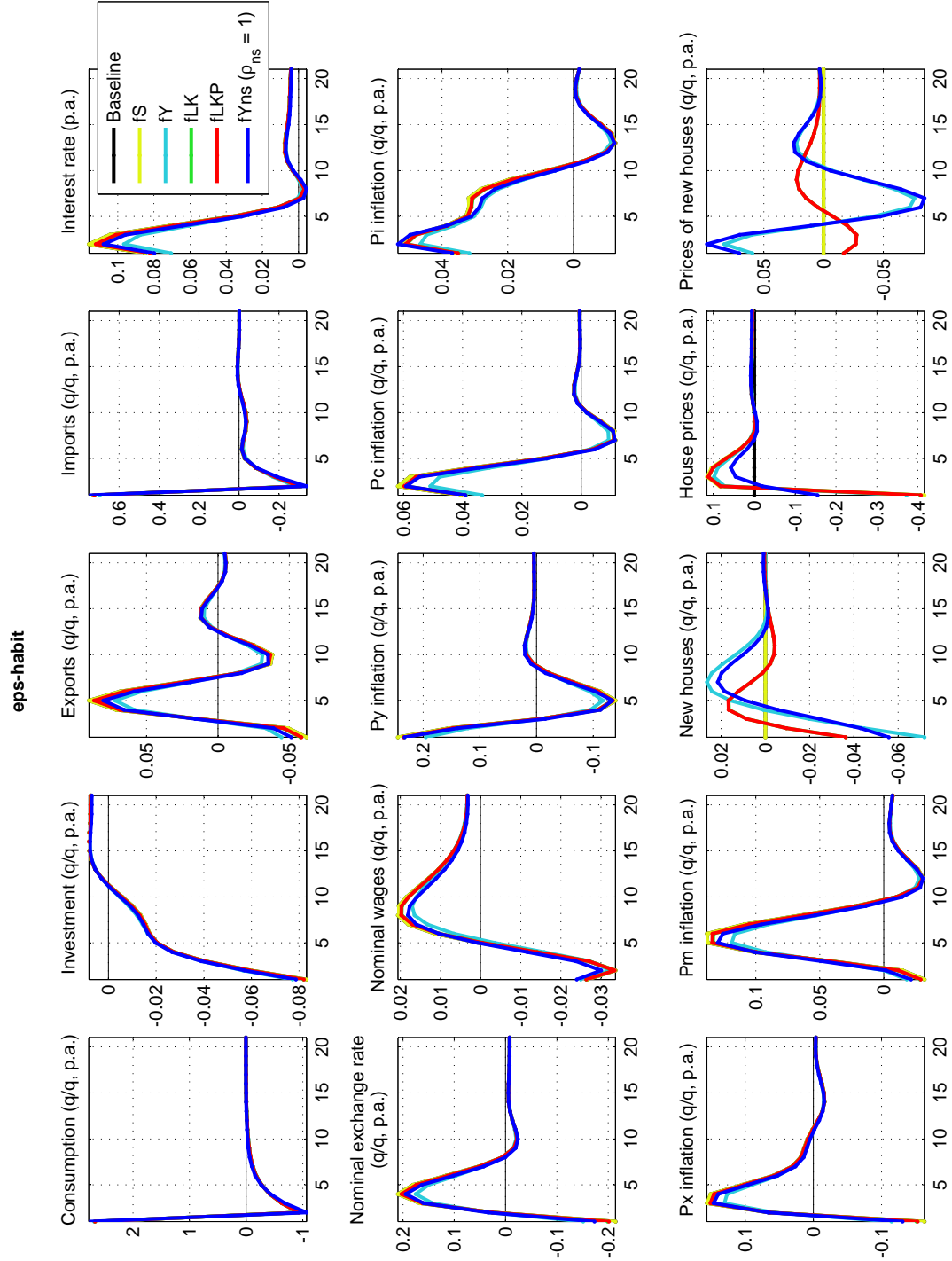


Figure B.3: TFP Shock

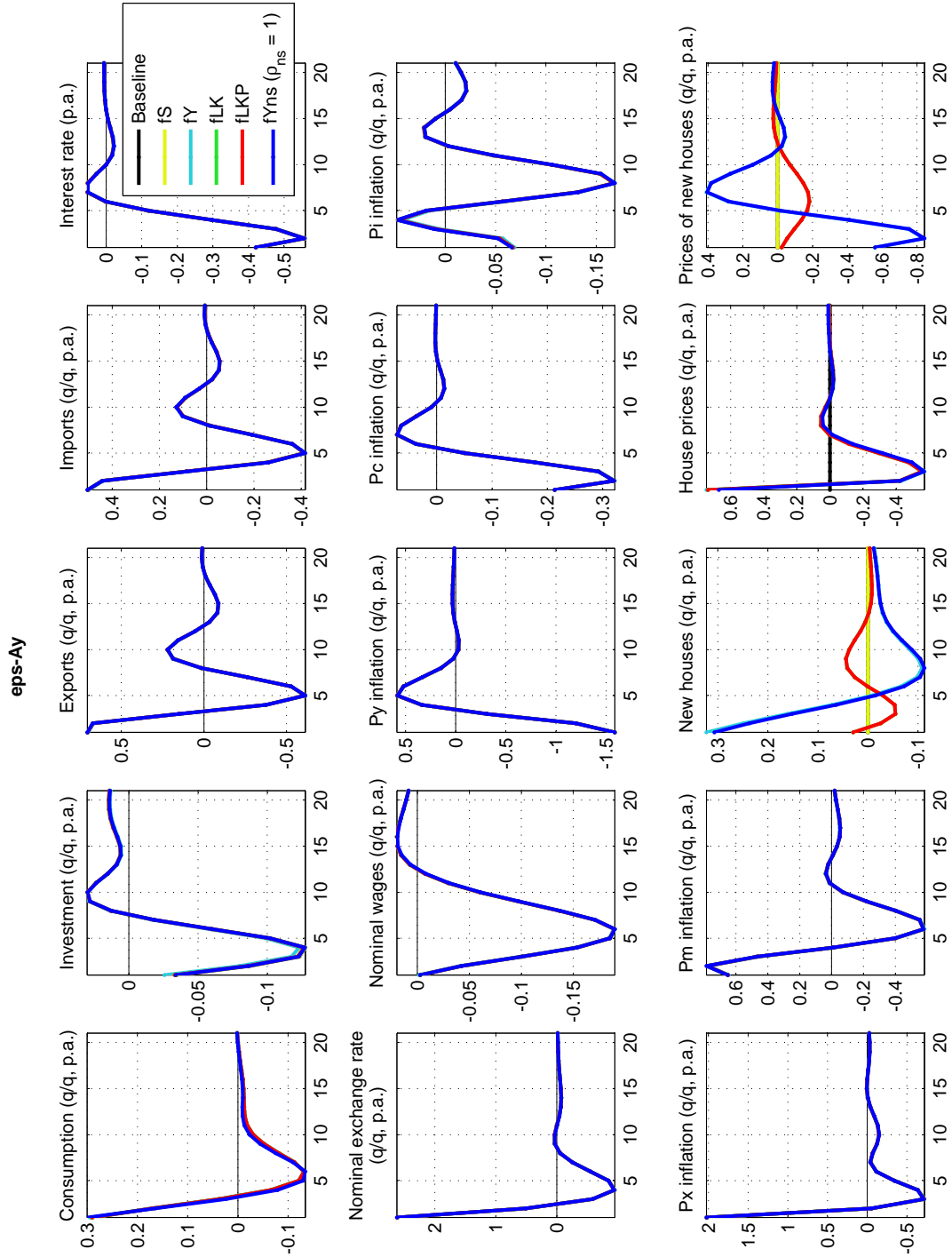




Figure B.4: Cost-Push Shock to Headline Inflation

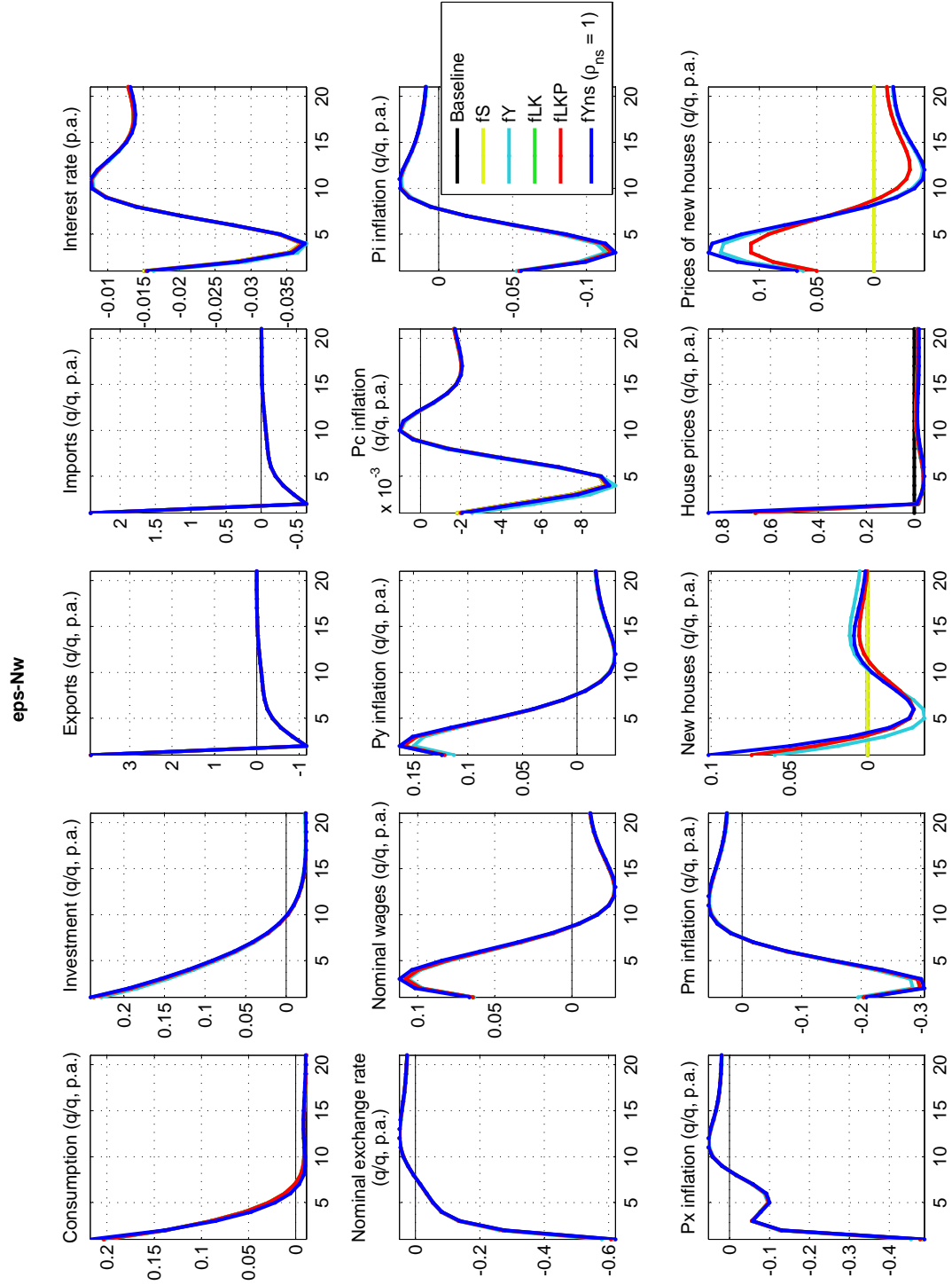


Figure B.5: Wage-Push Shock

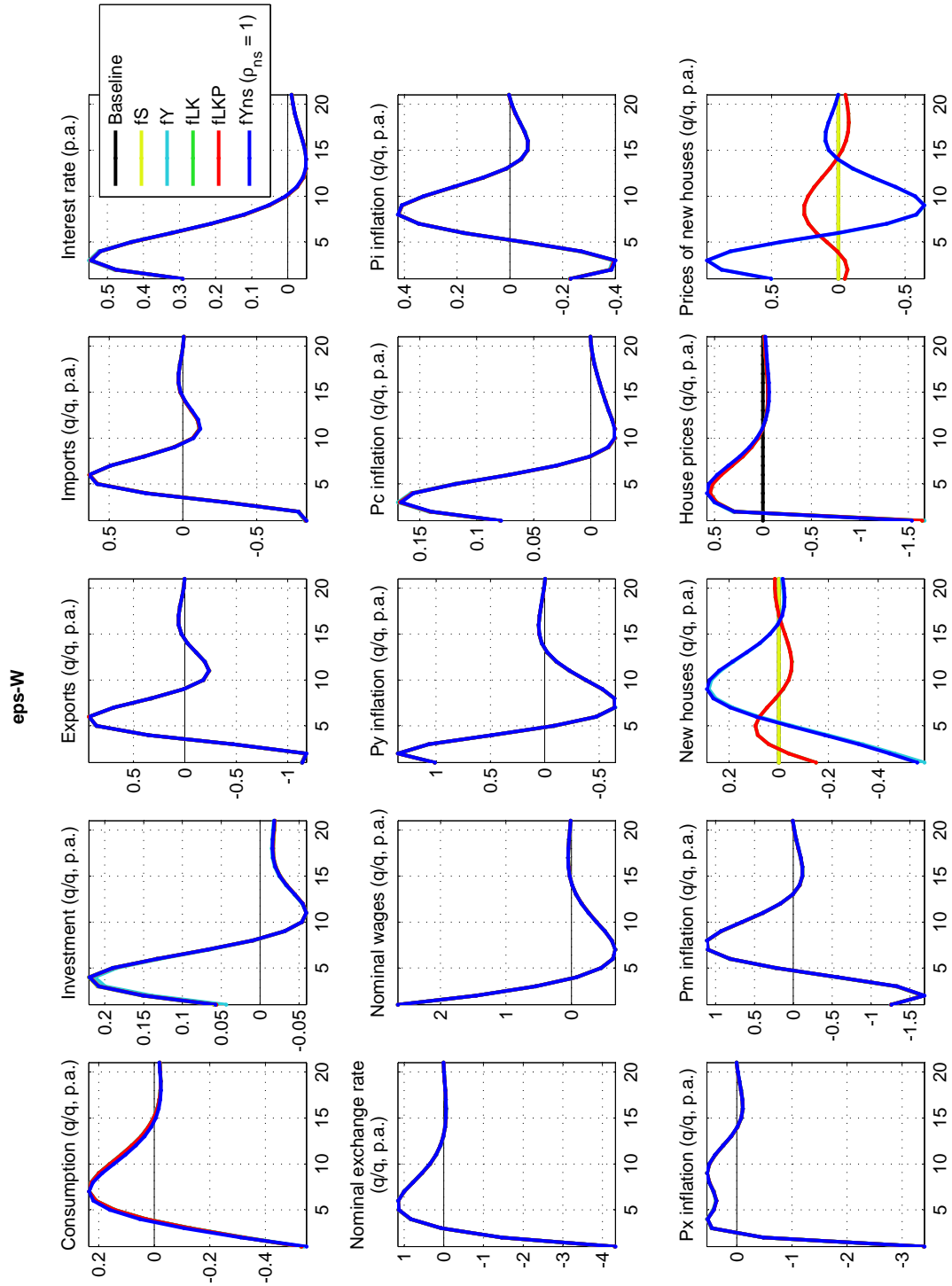


Figure B.6: UIP Shock

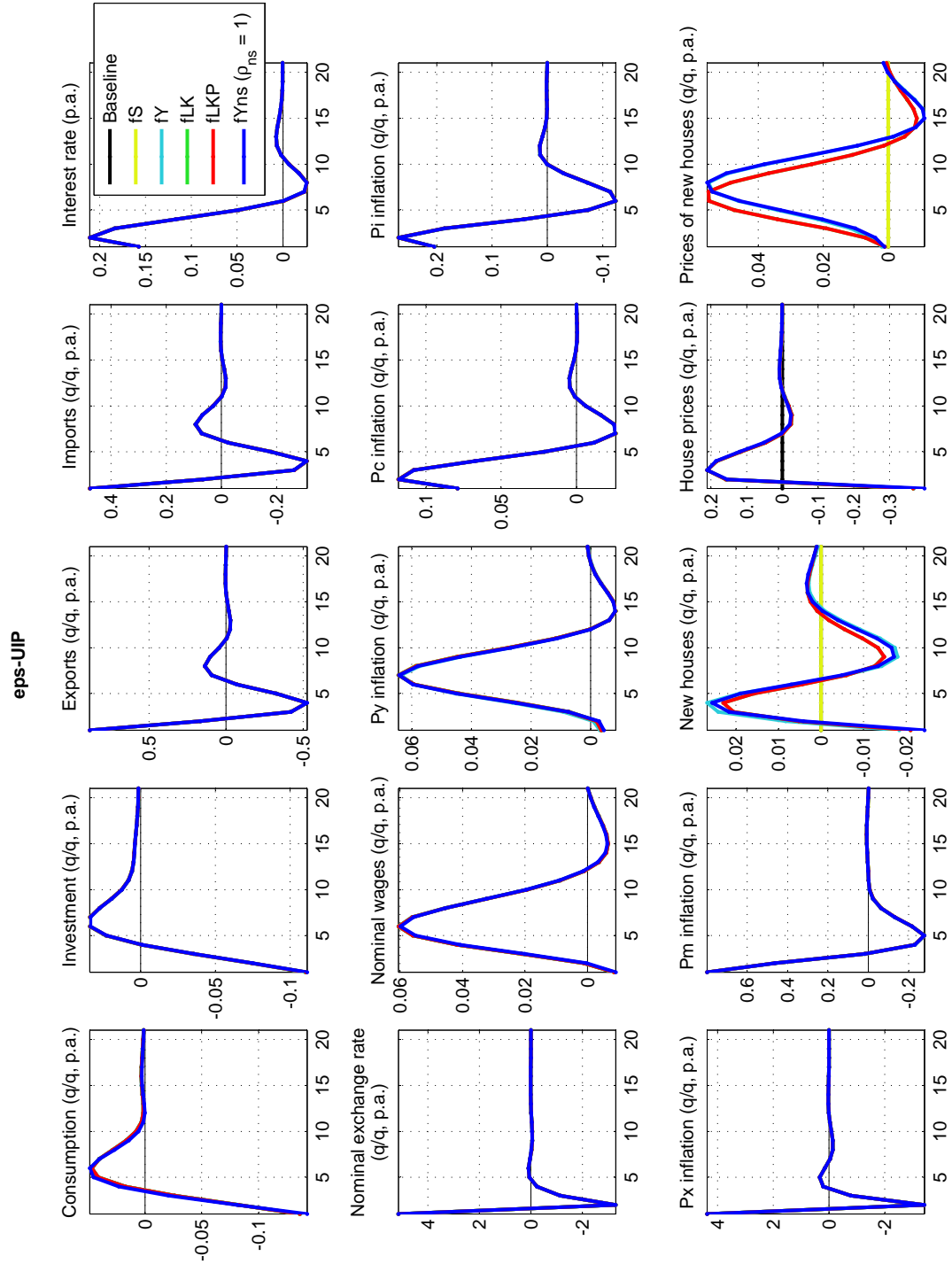


Figure B.7: Foreign Interest Rate Shock

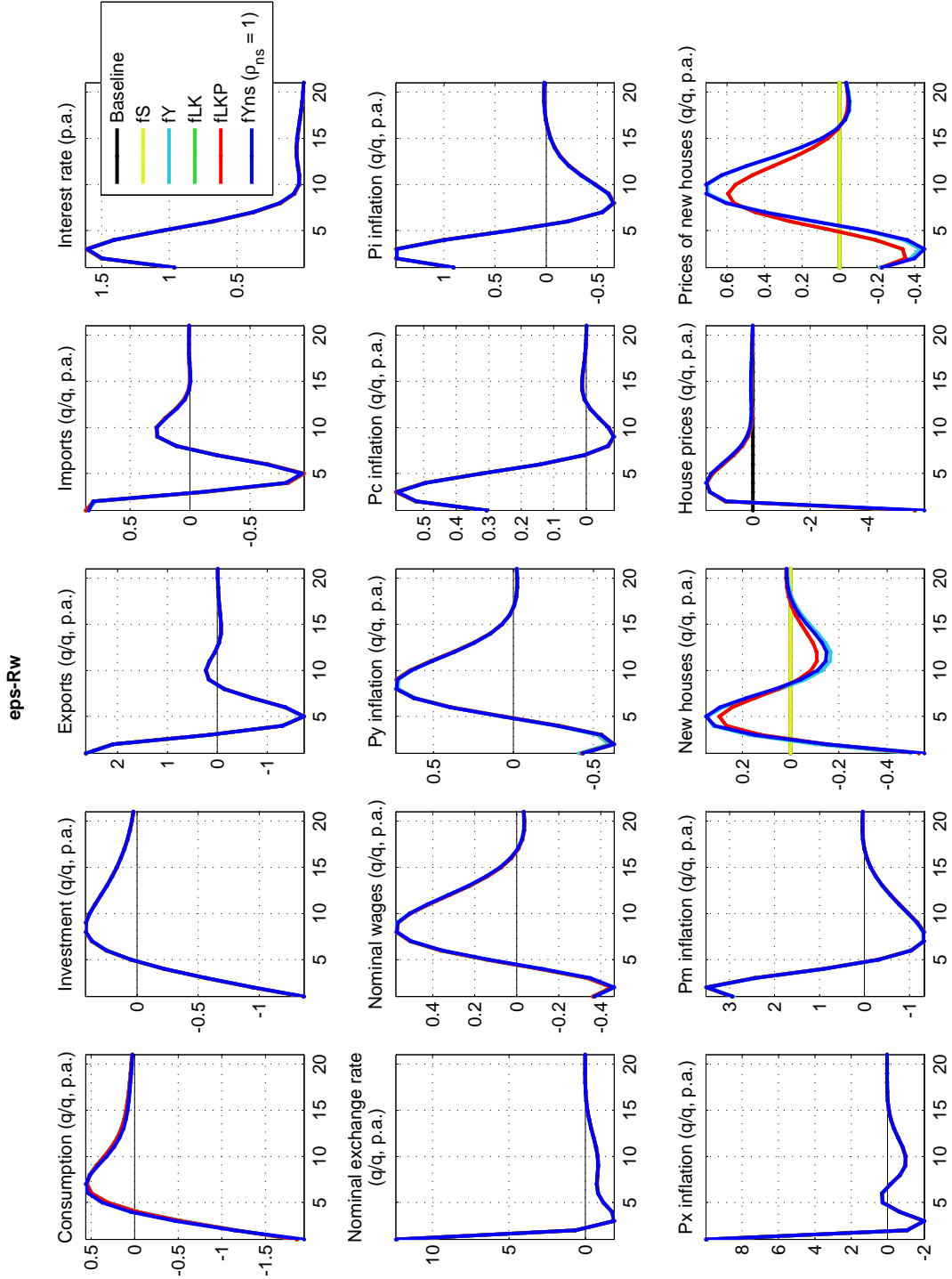


Figure B.8: Foreign Cost-Push Shock

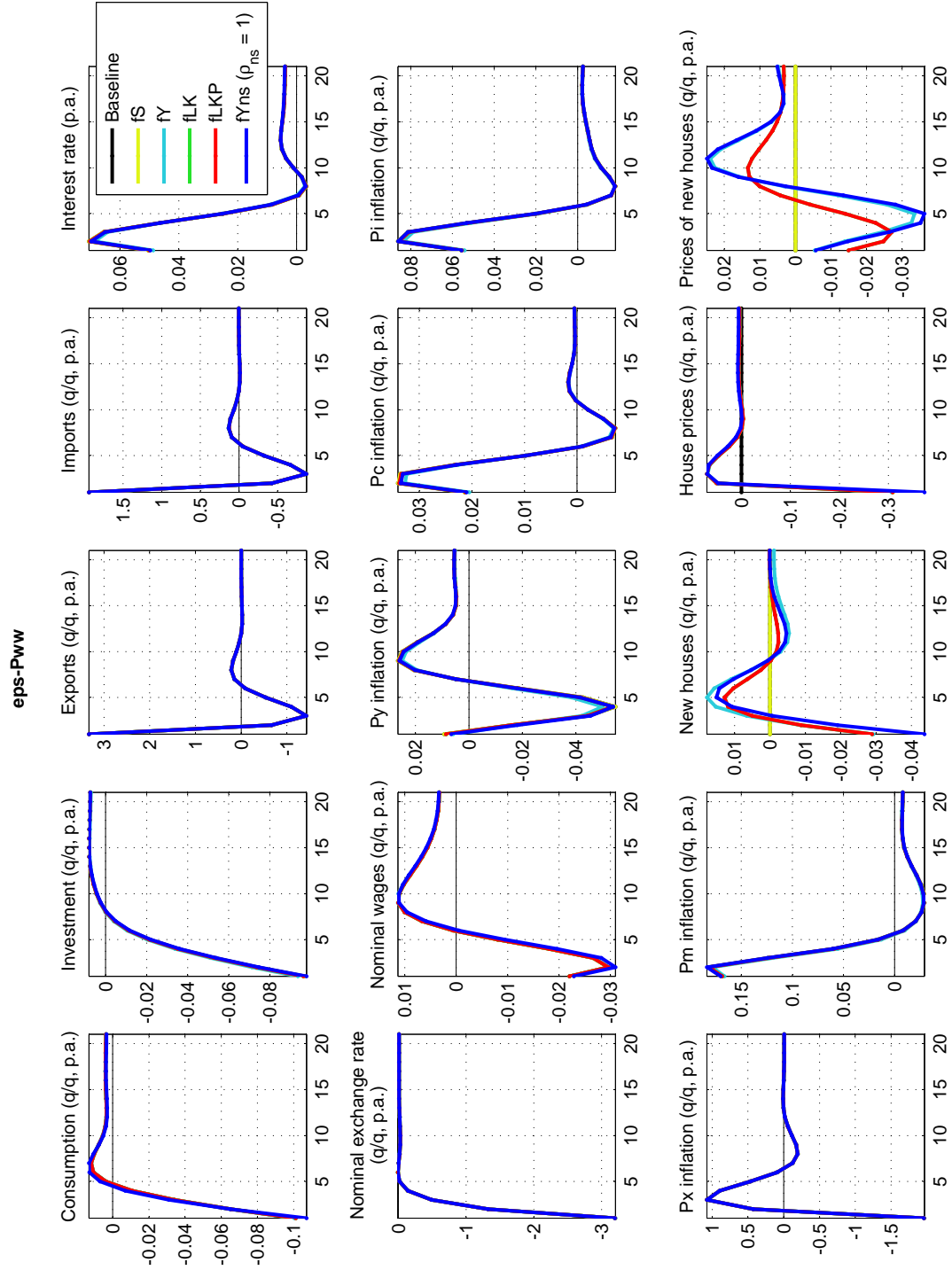


Figure B.9: Foreign Demand Shock

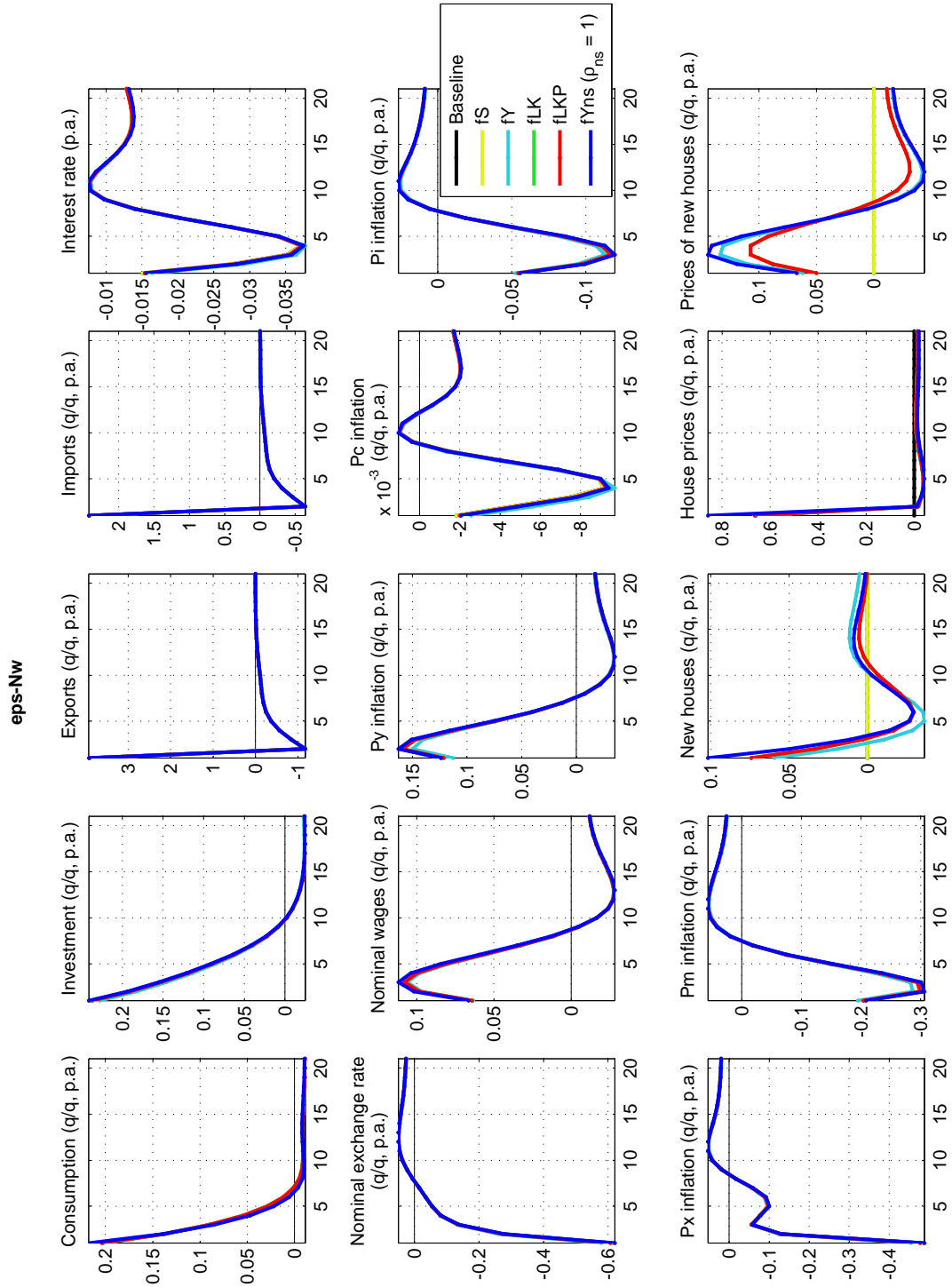


Figure B.10: Shock to the Discount Factor

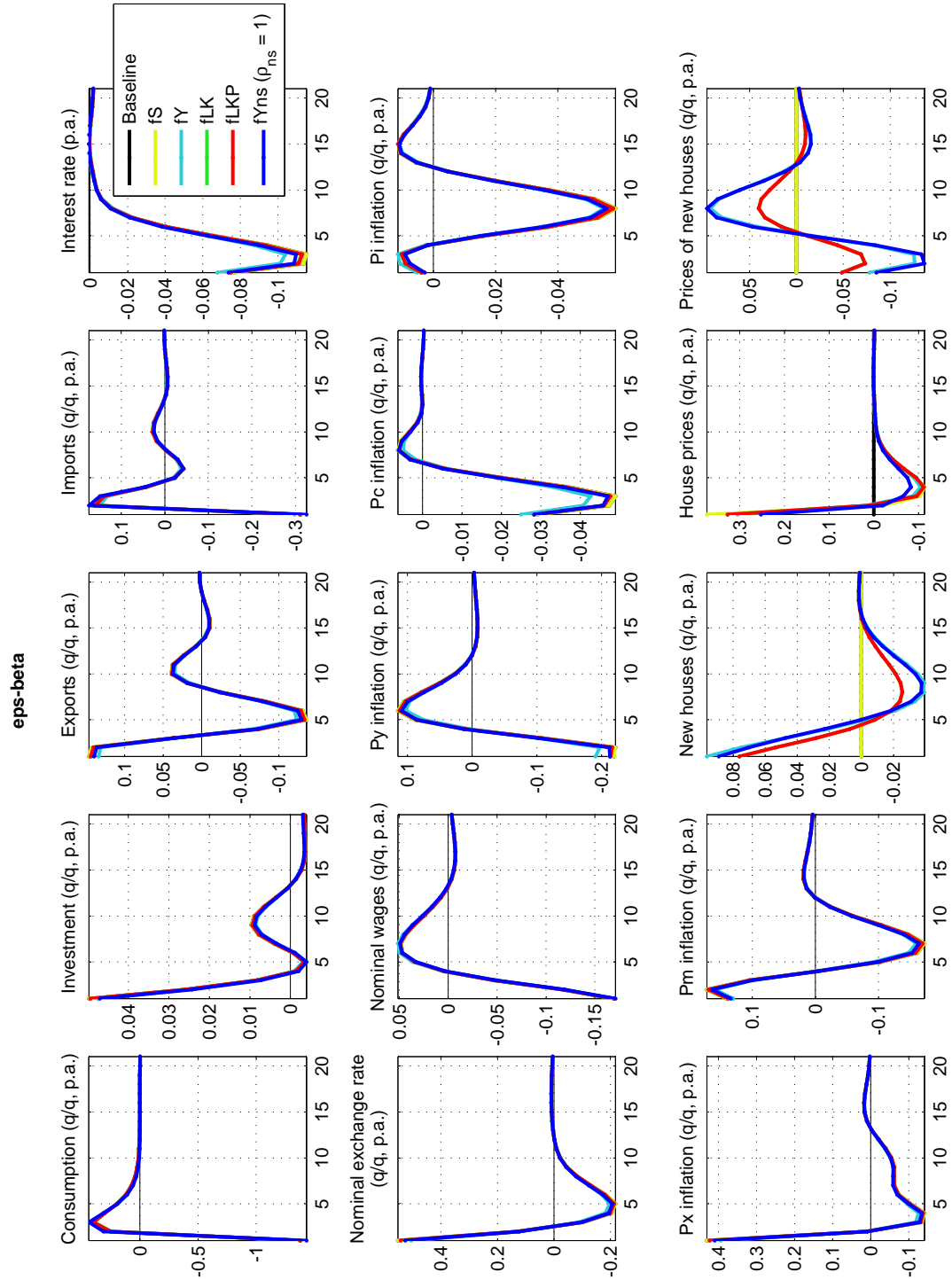


Figure B.11: Housing Preference Shock

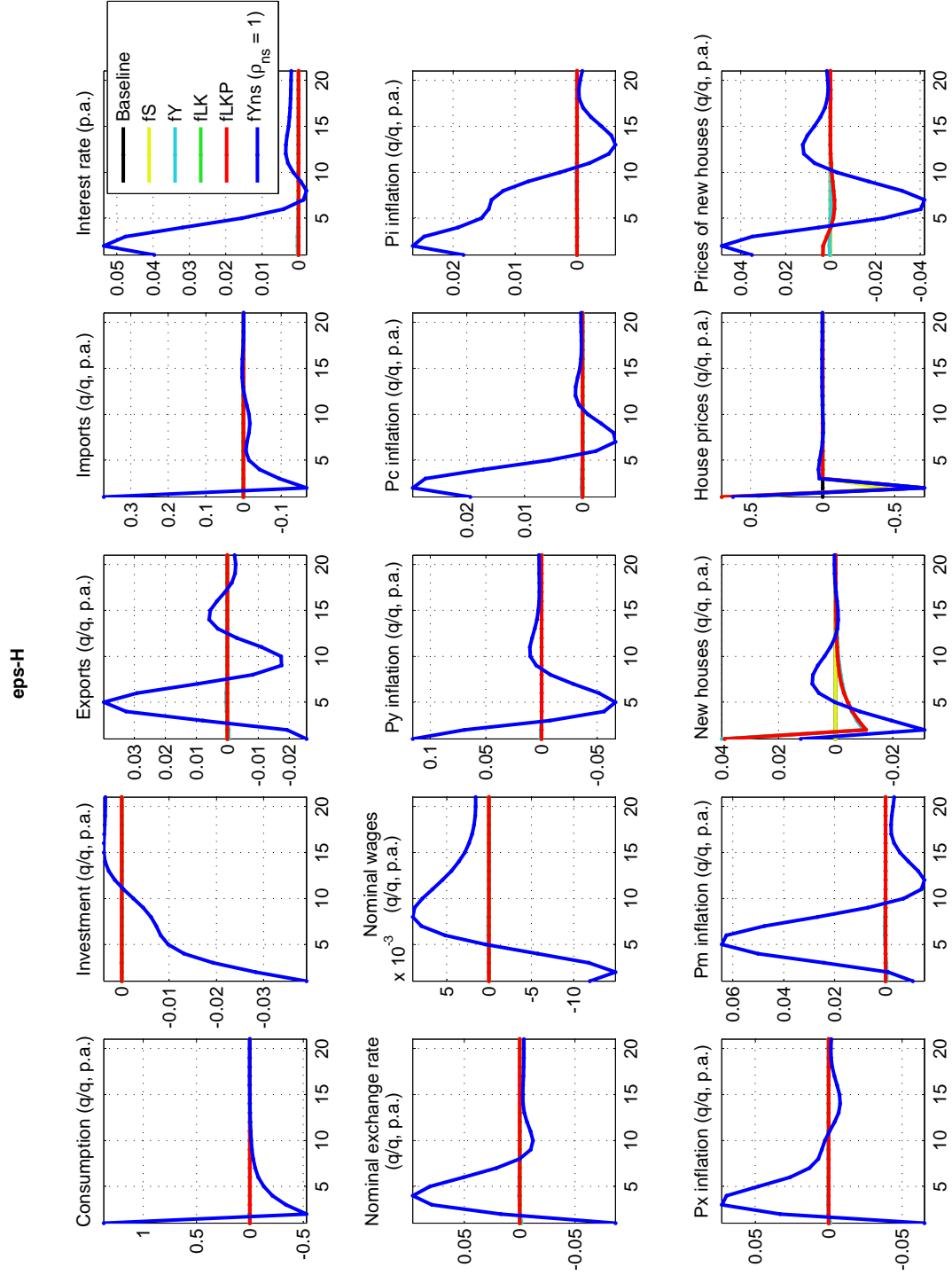




Figure B.12: Shock to Prices of New Houses

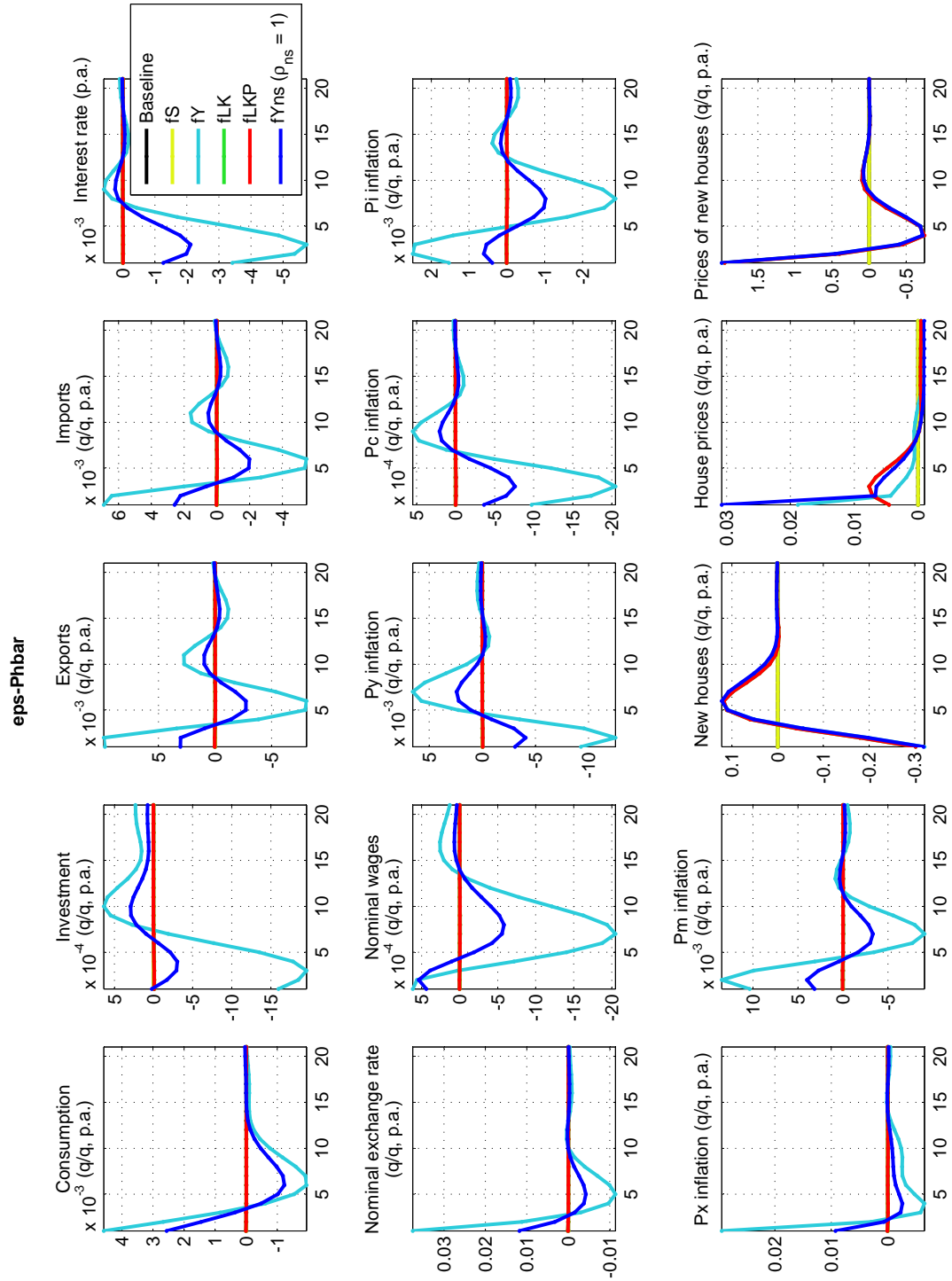


Figure B.13: Shock to House Technology

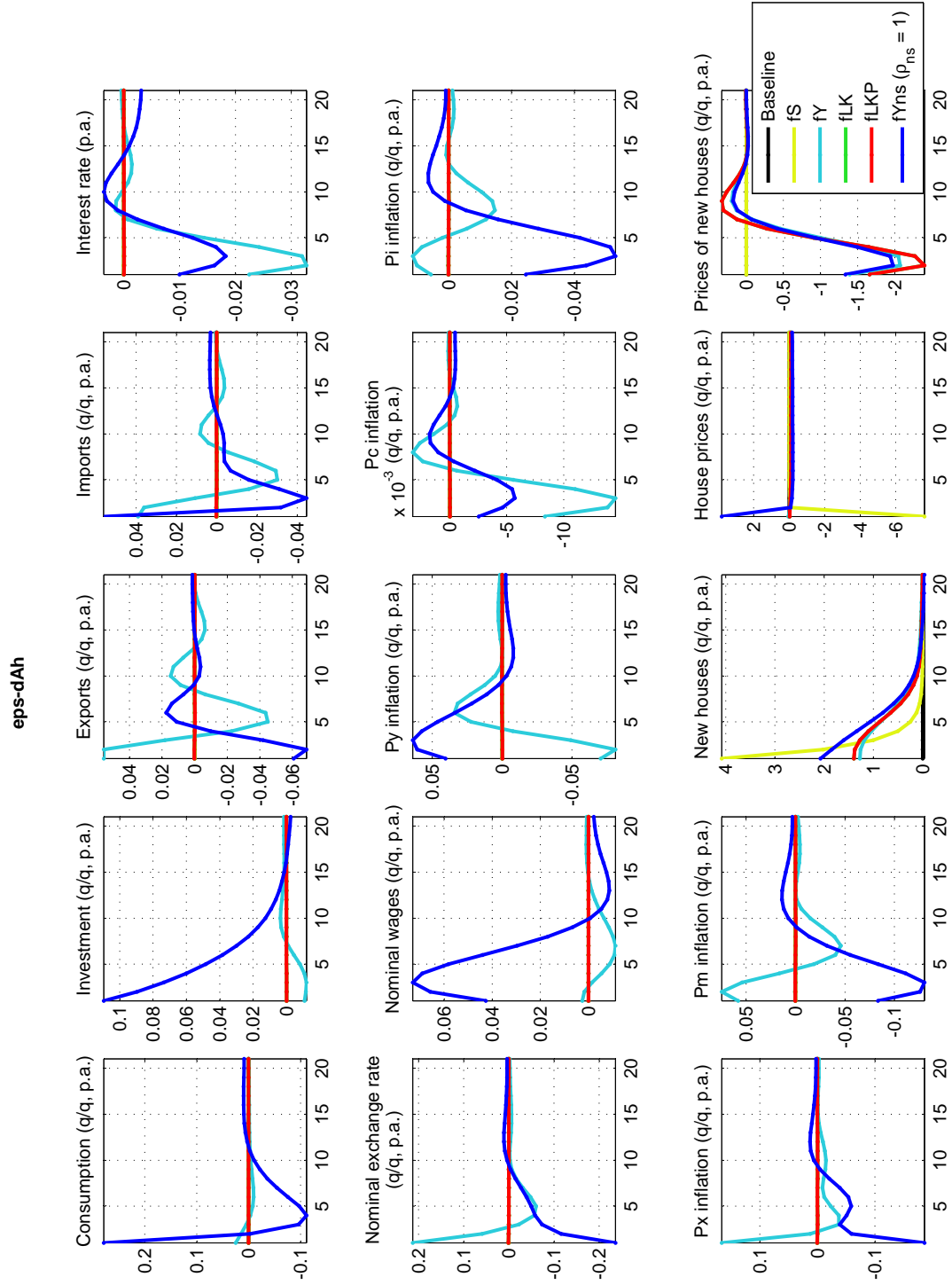


Figure B.14: Labour-Augmenting Technology Shock under Different Values of  $\eta$  (Model fY)

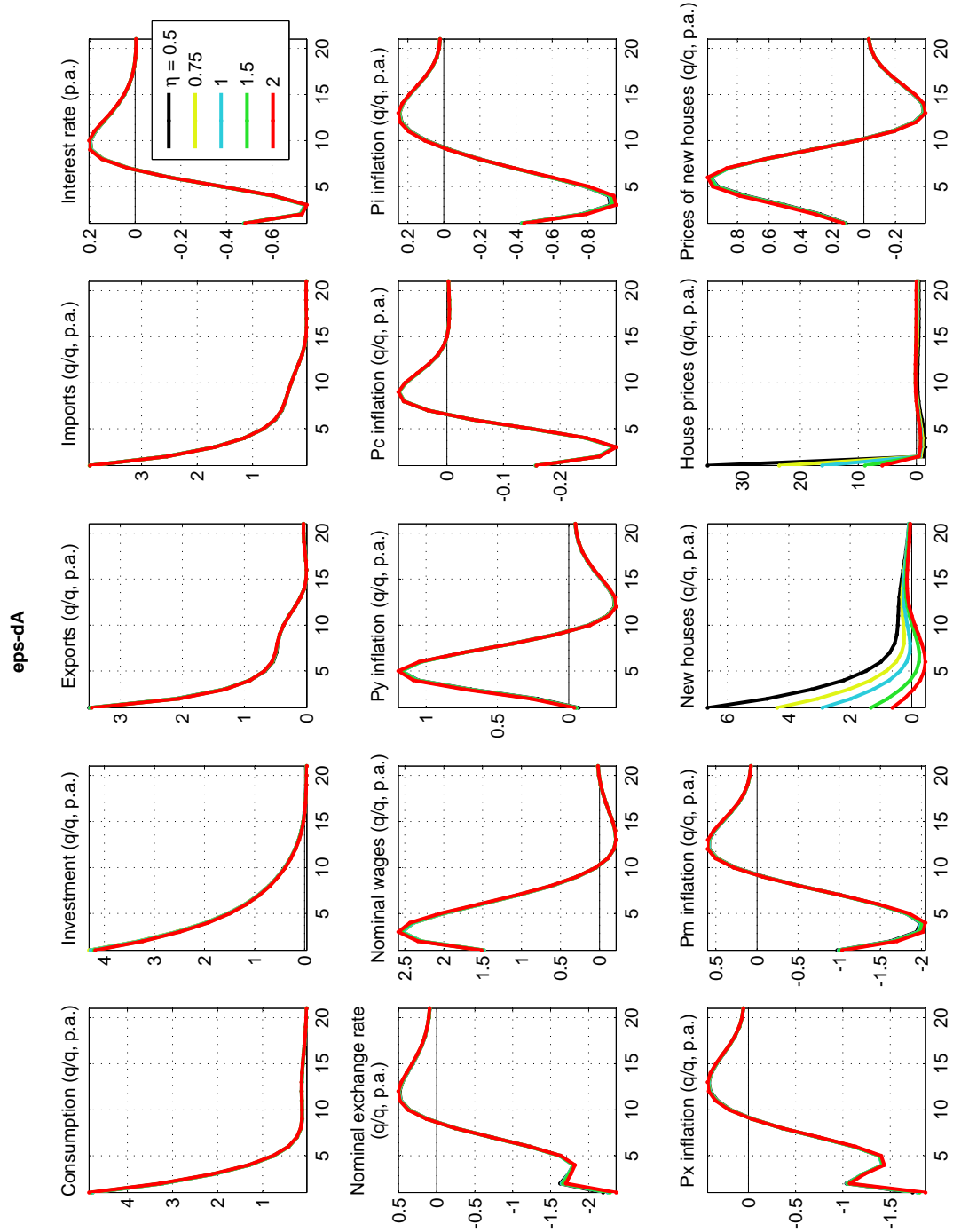


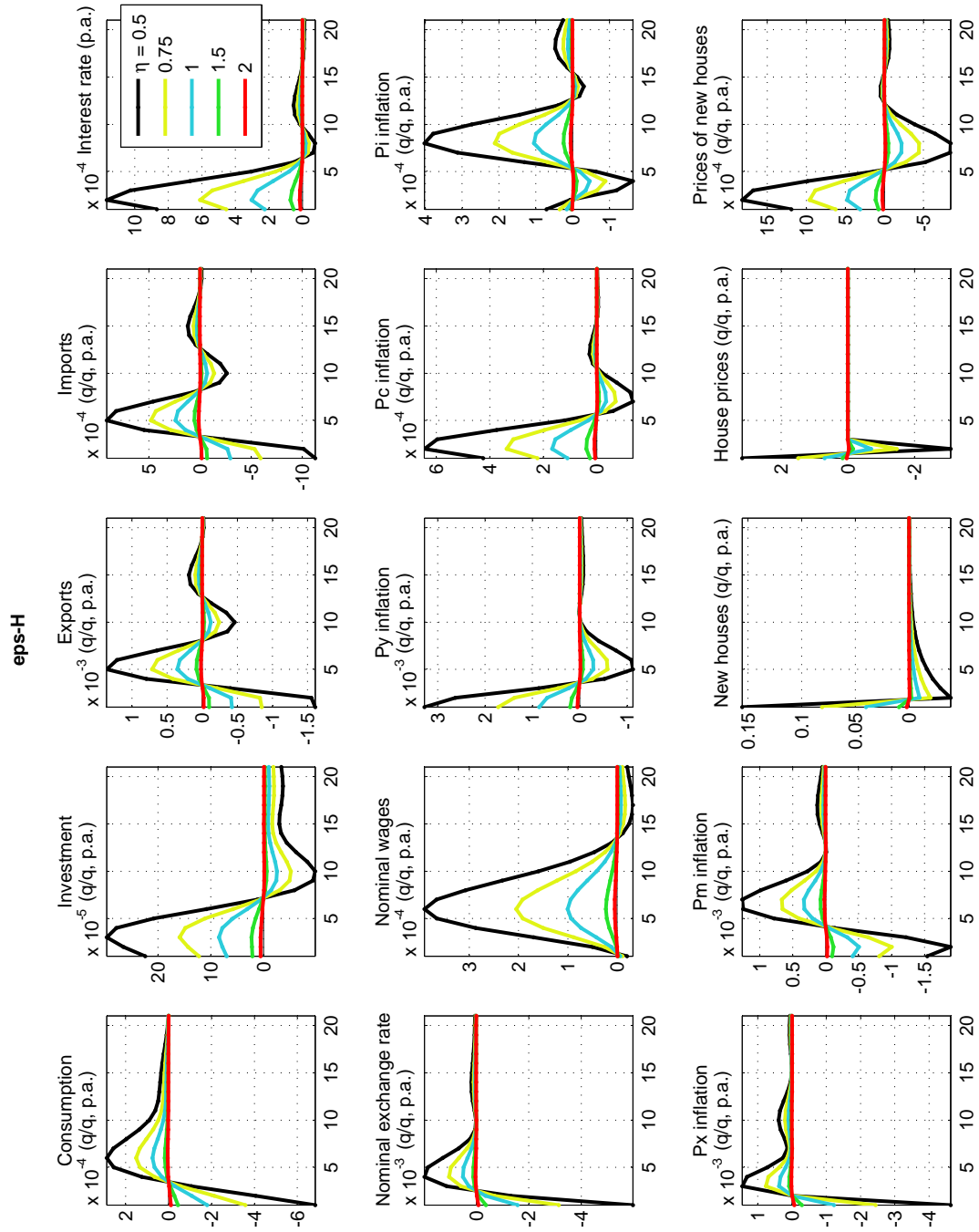
Figure B.15: Housing Preference Shock under Different Values of  $\eta$  (Model fY)

Figure B.16: Correlation of House Prices with Selected Variables

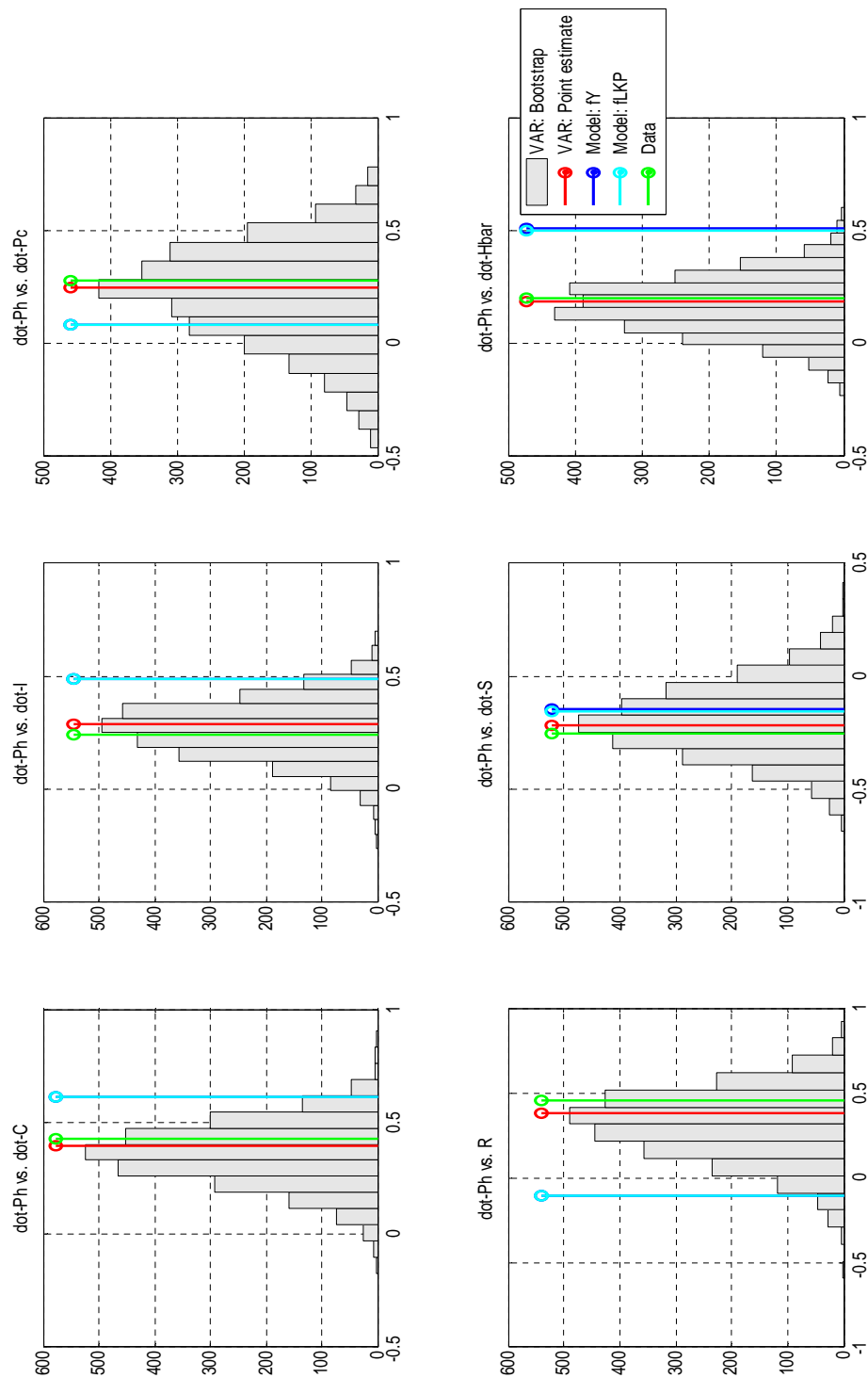


Figure B.17: Correlation of New Houses with Selected Variables

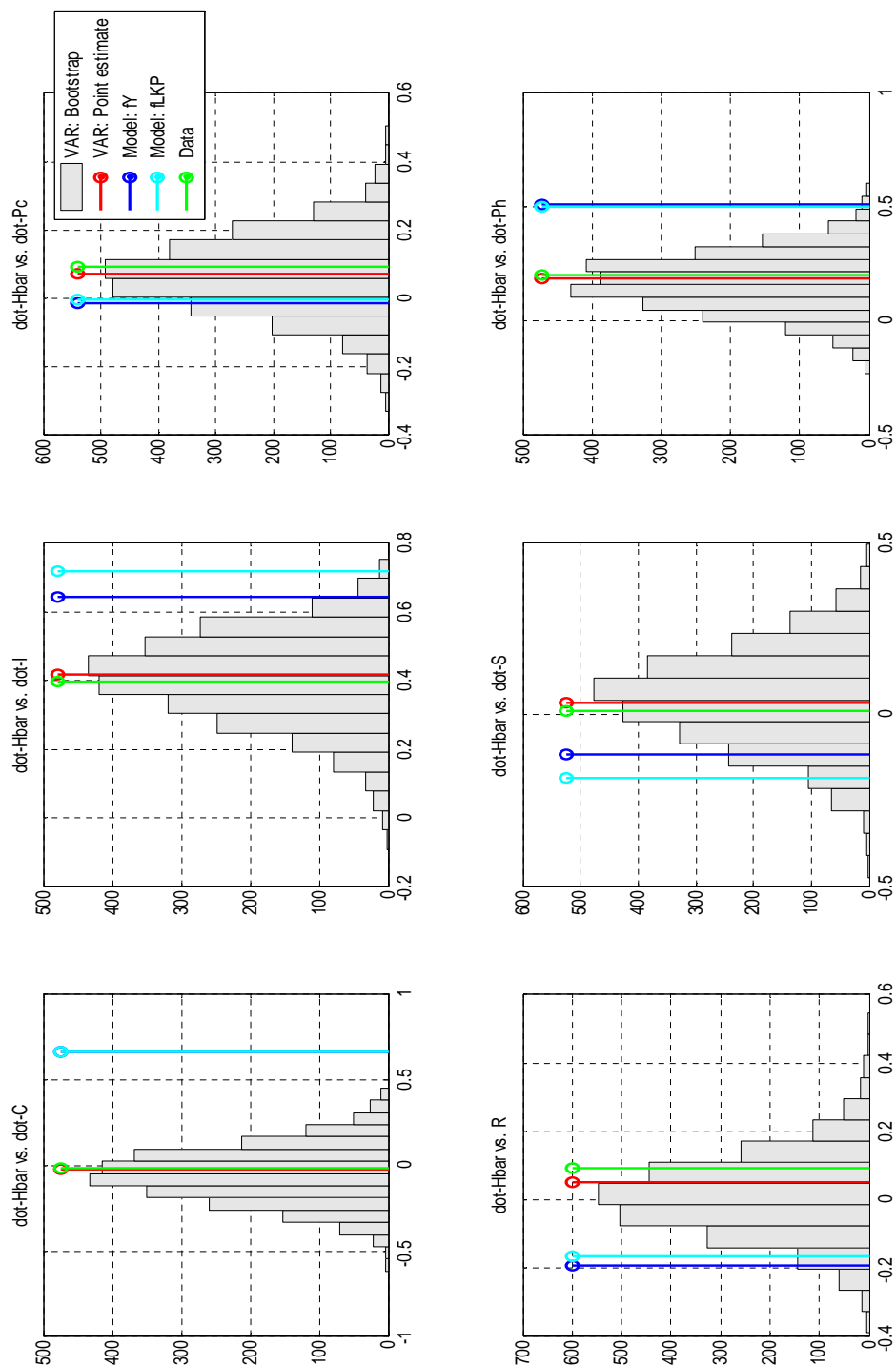
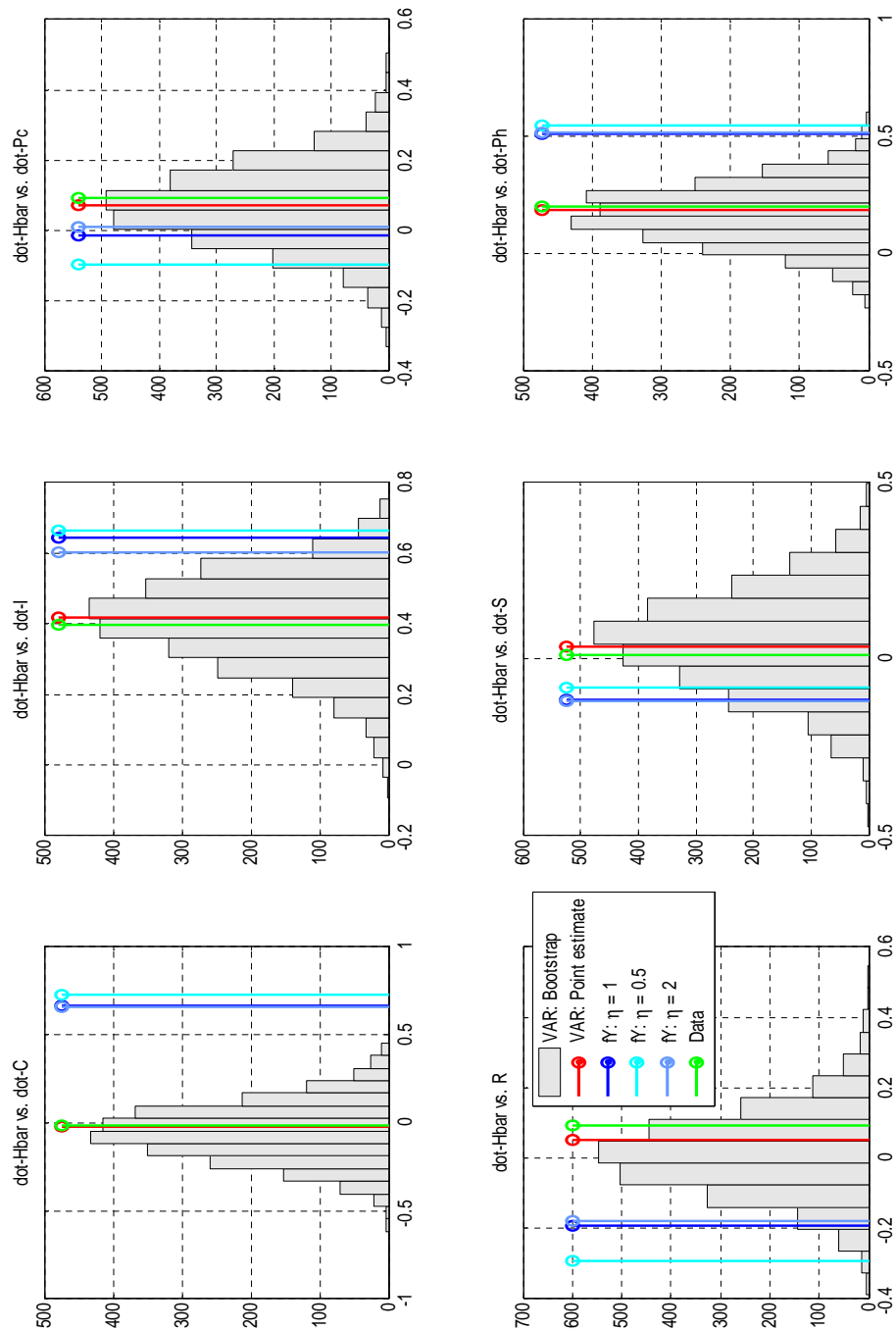


Figure B.18: Correlation of New Houses with Selected Variables (Various Values of  $\eta$ )



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