Housing and the Business Cycle Revisited

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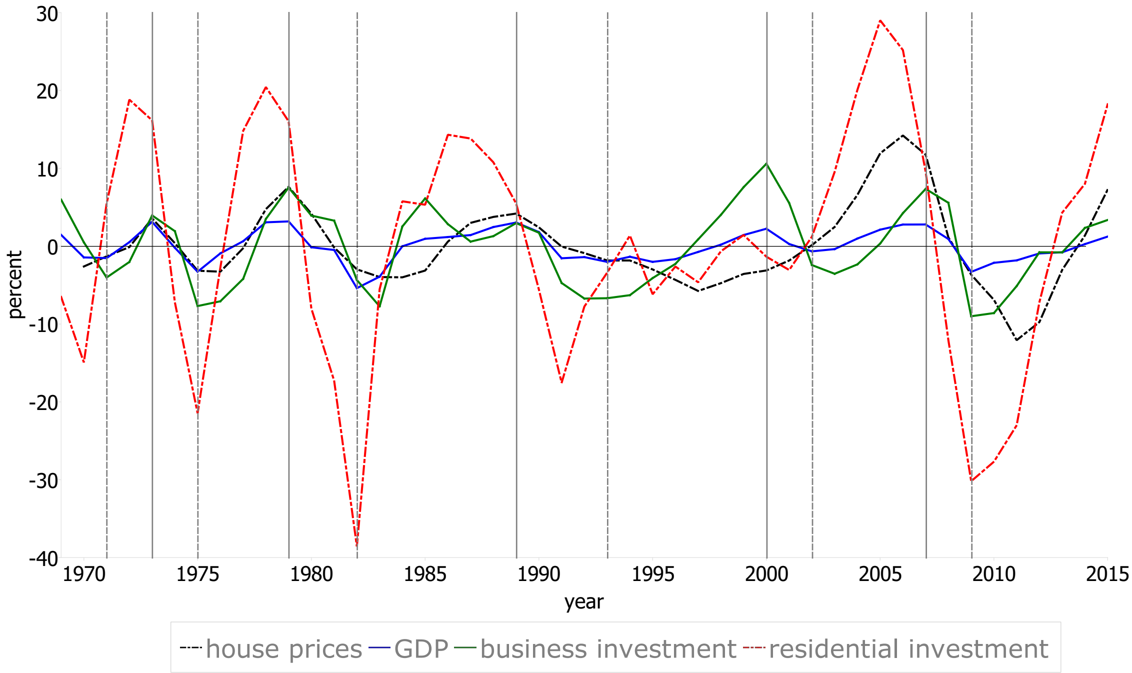
Abstract

I present a multisectoral DSGE model with housing, real frictions, and variable capital utilization that generates aggregate and sectoral co-movements due to uncorrelated sector-specific shocks. Major advances are the robust positive correlations of residential investment with house prices and business investment. In addition, business investment is lagging other economic activities. The key improvements are adjustment costs to business investment. I identify the parameters of the exogenous shock processes, business adjustment costs, and variable capital utilization with Bayesian estimation; the results confirm those obtained from earlier work in this field.

1 Introduction

Aggregate and sectoral co-movements are central features of business cycles. With respect to the housing sector, Davis and Heathcote (2005) (DH hereafter) point out three stylized facts: (i) gross domestic product (GDP), private consumption expenditure (PCE), business and residential investment, as well as house prices are positively correlated, (ii) residential investment is more than twice as volatile as business investment, and (iii) business investment lags GDP whereas residential investment leads GDP. Kydland et al. (2016), Davis and Nieuwerburgh (2015), Iacoviello and Neri (2010), and Iacoviello (2010) corroborate these findings. Figure 1 displays the cyclical components of GDP, house prices, as well as residential and business investment and verifies that the facts (i)-(iii) still characterize the cyclical properties. The co-movements, the volatility ratio between residential and business investment, the lead-lag pattern, and the housing boom-bust cycle are identifiable.

Figure 1: Cyclical behavior of different investment types, house prices and GDP



Notes: Cyclical component from per capita logged hp-filtered data with filter weight 100. Straight lines indicate a peak in GDP within min. ±2 years, dashed lines indicate a minimum in GDP within min. ±2 years. House prices are only available since 1970.

This paper presents a multisector DSGE model and examines the extent to which investment adjustment cost and variable capital utilization in the different sectors can account for the observed stylized facts. My starting point is the model of DH. It has had a lasting impact on the housing literature over the last decade. The model is able to explain the positive co-movements of aggregate and sectoral quantities and the volatility ratio of the investment types. It fails to predict the positive correlation between residential investment and house prices as well as the lead-lag pattern of residential and business investment.

The DH model distinguishes three sectors of production. In each sector, labor augmenting technical progress grows at a sector-specific rate and is subject to sector-specific stationary shocks generated by a three-dimensional, first-order vector-autoregressive process (VAR(1)). As I will demonstrate below, the correlation between the sectoral shocks is responsible for the model's ability to replicate some of the stylized facts. In particular, with sectoral uncorrelated shocks the co-movement between the sectoral outputs and all co-movements concerning residential investment weaken. Most notable, the model predicts a highly negative correlation between house prices and residential investment and fails to predict the positive co-movement between business and residential investment.

The multisector DSGE model presented here is an extended version of the DH model with sectoral uncorrelated shocks that accounts for the stylized fact (i), in the sense of stronger positive correlations concerning residential investment, as well as for (ii). It also partly replicates the lead of residential over business investment. Furthermore, business investment lags GDP. As the DH model, however, it fails to mimic the high volatility of house prices. Furthermore, the co-movements between the sectoral outputs remain weak.

While it is possible that productivity shocks are correlated across sectors as a result of common technological innovation or spillover, there are at least three arguments in favor of uncorrelated sectoral shocks: parsimony, explanatory content, and accordance with econometric practice. The DH model with VAR(1)-process has nine more parameters than a model with sector-specific but uncorrelated AR(1)-processes. The VAR(1)-assumptions transfer part of the explanation of the stylized facts outside the model whereas the AR(1)-assumption has to rely on the endogenous propagation mechanism. Therefore, the latter opens the way to a deeper understanding of economic mechanisms than the former. Finally, considering the practice of structural vector autoregressive models, researchers seem to favor uncorrelated structural shocks.

The extensions vis-à-vis the DH model are in detail: variable capacity utilization as in Jaimovich and Rebelo (2009), adjustment costs to business investment as in Christiano et al. (2005) (CEE adjustment costs hereafter), sectoral frictions in the allocation of capital as in Boldrin et al. (2001), and, finally, higher costs of accumulating homes due to an increased share of land in the production of new houses. Bayesian inference, using the Solow residuals found by DH as observables, provides the estimates of the parameters of the three independent AR(1)-processes that drive the model as well as the two unobservable parameters that are crucial for the propagation of these shocks.

To understand the contribution of each of these ingredients, consider a shock to labor augmenting technical progress in one of the three sectors. The supply of goods produced in this sector will increase as well as the demand of labor and capital services employed in this sector. At the final stage of production, the price of that good decreases that has a higher cost share of the respective input. For instance, since manufacturing goods have approximately the same cost share in the production of consumption goods (see Table 1) and housing investment, the price effect of a shock in the manufacturing sector is limited. On the other hand, a shock to the construction sector will decrease the price of housing investment whereas a shock to the service sector will decrease the price of consumption goods. Adjustment costs to housing and business investment limit the effects of price changes on the respective demand so that the income effects of the shock prevail and consumption, residential and business investment will move together. Variable capacity utilization enhances the income effects and, thus, strengthens the co-movements between the major macroeconomic aggregates. It also acts as a substitute for limited sectoral capital mobility, which, therefore, contributes little to the model's ability to mimic the stylized facts. CEE adjustment costs penalize rapid changes between current and past investment so that business investment lags GDP.

The paper relates to the growing literature on housing and the business cycle, comprehensively reviewed by Davis and Nieuwerburgh (2015), as well as to the literature on multisectoral real business cycle models.

Jaimovich and Rebelo (2009) designate the ability of a model to reproduce co-movements between sectoral and aggregate economic quantities as a litmus test. Nevertheless, most models fail this test. Early attempts by Benhabib et al. (1991), Greenwood and Hercowitz (1991) and Fisher (1997) examine the co-movement problem in models with market and home production. They find that investment in market and home capital correlate negatively. Gomme et al. (2001) assume that market capital requires more time to be built than home capital and partly succeed in explaining that investment in market capital lags investment in home capital. Fisher (2007) chooses another approach. He solves the lead-lag puzzle by modeling home capital as a complement of market production. Khan and

Rouillard (2016) show that his approach requires implausibly high capital tax rates. My approach differs in the propagation channel: housing and productive capital are not complements, but adjustment costs disable the substitution. This approach is in line with Chang (2000) and, in a broader sense, with limited capital mobility as in Boldrin et al. (2001). Furthermore, as shown by Lucca (2007), CEE adjustment costs are, to a first-order linear approximation, equivalent to a more sophisticated time-to-build model of capital accumulation.

Kydland et al. (2016) investigate the stylized facts (i)-(iii) in a one-sector model with nominal and real frictions. The latter take the form of a concave production possibilities frontier and a convex increasing transformation rate of output to new houses. They can be seen as a reduced form of the multisectoral supply-side of DH to account for (ii). Kydland et al. (2016) successfully replicate that residential investment leads the business cycle albeit the nominal interest rate, which drives this result, is exogenously linked with a lead to the business cycle.

Khan and Rouillard (2018) explore the role of residential investment as a collateral to finance consumption. They calibrate the model for the time period following the U.S. financial reforms in the early 1980s and show that residential investment leads the business cycle to finance future consumption. Figure 1, however, indicates that residential investment also leads the business cycle before the financial reforms.

To account for the large house price volatility, Dorofeenko et al. (2014) introduce CEE adjustment costs in business and residential investment as well as default risk in the DH framework. Furthermore, they adopt the exogenous process with correlated shocks. The model tends to the opposite direction of the lead-lag pattern as empirically observed and it is not clear which parts are driven endogenously.

As in Dorofeenko et al. (2014), many papers have tried to explain the large volatility of house prices and the boom-bust cycle in the first decade of the 21st century (see, e.g. Favilukis et al. (2017) and the review paper of Davis and Nieuwerburgh (2015)). These models consider, amongst other factors, heterogeneous agents, risk shocks, and financial frictions. All of these ingredients are beyond the scope of the present model that does not aim to contribute to this debate.

The remainder of the paper is organized as follows. Section 2 introduces the model and stresses the differences in the investment and capital types. Section 3 explains the calibration and estimation strategy, presents the results in form of second moments and discusses the robustness of these findings. Section 4 concludes. An Appendix covers additional material: the system of equations that determines the model's dynamics, further results, descriptions of the data and the Monte-Carlo-algorithms.

2 THE MODEL

The model builds on a stripped-down version of the DH model from which I borrow the nomenclature. The economy consists of a representative household and three representative firms, one in an intermediary stage of production, one in the production of investment and consumption goods, and one in the production of new homes. Different from DH, there is no government sector and no population growth. All quantities are in per capita terms. Time t is discrete and one period is equivalent to one year.

2.1 Analytical Framework

Intermediary goods. The representative firm on the intermediary stage of production rents capital and labor from the household and produces three kinds of goods X_{it}, where $i \in \{b, m, s\}$ denotes the construction good, the manufacturing good, and the service good, respectively. The production function for each good is Cobb-Douglas with constant returns to scale:

$$X_{it} = (u_{it} K_{it})^{\theta_i} (A_{it} N_{it})^{1-\theta_i}, \quad \theta_i \in (0, 1), \tag{1}$$

where u_{it} is the utilization rate of capital K_{it} in the production of good i, N_{it} is raw labor and A_{it} its efficiency factor. The efficiency of labor is specific to the production of good i and involves a deterministic trend and a stationary stochastic component:

$$\ln(A_{it}) = \ln(A_{i0}) + t \ln(g_{A_i}) + z_{it}, \tag{2}$$

$$z_{it} = \rho_i z_{it-1} + \epsilon_{it}, \quad \epsilon_{it} \overset{\text{iid}}{\sim} \mathcal{N}(0, \sigma_i^2). \tag{3}$$

The innovations ϵ_{it} are uncorrelated in time and between the different technologies.

Let P_{it}, r_{it}, and W_t denote, respectively, the price of good i, the rental rate of capital services, and the real wage. The firm chooses $u_{it} K_{it}$ and N_{it} to maximize profits Π_{It}, given by

$$\Pi_{It} := \sum_{i \in \{b,m,s\}} [P_{it} X_{it} - r_{it} u_{it} K_{it} - W_t N_{it}]$$

subject to the production functions (1).

Consumption and investment goods. At the final stage of production, a firm employs the intermediary goods to produce two goods $j \in \{c, d\}$. The good d is residential investment, and the good c is used for consumption and business investment. The latter serves as numéraire and the relative price of good d is denoted by P_{dt}. The production function of each good is again Cobb-Douglas with constant returns to scale:

$$Y_{jt} = X_{bjt}^{B_j} X_{mjt}^{M_j} X_{sjt}^{S_j}, \quad B_j + M_j + S_j = 1, \tag{4}$$

where X_{ijt} is the amount of intermediary good i employed in the production of the final good j. The firm's profits are given by:

$$\Pi_{Ft} := Y_{ct} + P_{dt} Y_{dt} - \sum_{i \in \{b,m,s\}} P_{it}(X_{ict} + X_{idt}).$$

The firm chooses X_{ijt} to maximize Π_{Ft} subject to the production technologies (4).

Housing. At the final stage of production a firm combines land l_t and residential investment goods Y_{dt} to produce new homes Y_{ht} according to

$$Y_{ht} = Y_{dt}^{1-\phi} l_t^{\phi}, \quad \phi \in (0,1). \tag{5}$$

New homes Y_{ht} replace depreciated houses $\delta_h H_t$ and increase the stock of existing houses H_{t+1} in the usual manner:

$$H_{t+1} = (1 - \delta_h) H_t + Y_{ht}. \tag{6}$$

The household supplies a fixed amount of land $l_t \equiv 1$ at the price P_{lt}. Fixed land introduces convex adjustment costs to the quantity of new homes. With a price of new homes P_{ht} the firm solves

$$\max_{Y_{dt},l_t} \quad \Pi_{Ht} := P_{ht}Y_{ht} - P_{dt}Y_{dt} - P_{lt}l_t$$

subject to the production function (5).

Household. The household maximizes expected life-time utility given by:

$$U_t := \mathbb{E}\sum_{s=0}^{\infty}\beta^s u(C_{t+s}, H_{t+s}, 1-N_{t+s}).$$

His current-period utility u depends on consumption C_t, the stock of houses H_t, and leisure $1-N_t$. It is parameterized as in DH:

$$u(C_t, H_t, 1-N_t) := \frac{1}{1-\sigma}\left[C_t^{\mu_c}H_t^{\mu_h}(1-N_t)^{1-\mu_c-\mu_h}\right]^{1-\sigma}.$$

The household faces costs of capital accumulation given by:

$$\sum_{i\in\{b,m,s\}} K_{it+1} = I_t\left(1-\varphi\left(\frac{I_t}{I_{t-1}}\right)\right) + \sum_{i\in\{b,m,s\}}(1-\delta_k(u_{it}))K_{it} \tag{7}$$

The function $\varphi(x_t)$ has the properties proposed by Christiano et al. (2005) and Jaimovich and Rebelo (2009), namely: $\varphi(x)=0$, $\varphi'(x)=0$, and $\varphi''(x)>0$, where x is the growth factor of investment on the balanced growth path. Thus, the replacement of capital on this path is costless.

The rates of capital depreciation $\delta_{k_{it}}$ depend on the degree of capital utilization u_{it}. As in Jaimovich and Rebelo (2009), the function δ_k satisfies $\delta_k'(u_{it})>0$, $\delta_k''(u_{it})\geq 0$, with the elasticity of $\delta_k'(u_{it})$ being constant.

The household must choose his effective supply of capital to sector i before the realization of the sectoral shocks while he can choose his supply of labor after the realization. Thus, the sectoral mobility of capital is limited, but not the mobility of labor. Besides the law of capital accumulation (7) and the accumulation of homes (6), the household's decision must satisfy his budget constraint:

$$C_t + I_t + P_{ht}Y_{ht} \leq P_{lt}l_t + \sum_{i\in\{b,m,s\}}\left[r_{it}u_{it}K_{it} + W_tN_{it}\right]. \tag{8}$$

The left-hand side represents the household's expenditure on consumption, business investment, and new homes. The right-hand side provides his income from labor, capital, and land.

National accounts. DH implement a hypothetical rental rate for housing denoted by Q_t to define consumption and GDP consistently with the National Income and Product Accounts (NIPA). This rate is equivalent to the marginal rate of substitution between consumption and housing. The equivalent to the NIPA PCE in the model is then the sum of consumption C_t and the rents for housing $Q_t H_t$. Accordingly, GDP Y_t is given by: $Y_t = PCE_t + I_t + P_{dt} Y_{dt}$.

2.2 The extensions at a glance

In the DH model, the beginning-of-period stock of market capital is fixed. Within the period, however, the services of this stock can freely move between the three sectors. In the present model, the beginning-of-period capital allocated to each sector is fixed, but the variable utilization rates substitute for the limited sectoral mobility of capital, albeit at the cost of variable depreciation rates. Housing capital, on the other hand, has a fixed utilization rate of one and, thus, its rate of depreciation is constant. This difference in treatment relates to differences in the nature of both kinds of capital. The operating time of equipment is less constrained by external factors than the use of housing services, which is limited by time spent at home, which, in turn, is determined by the decision to work. Furthermore, the depreciation of housing capital depends on climatic and other environmental conditions rather than on the utilization rate of housing. Nevertheless, I will study the robustness of my results with respect to a fixed utilization rate of housing capital.

There is a second difference between both kinds of capital which is related to the modeling of adjustment costs. The adjustment costs of market capital depend on the rate of change of investment, and, thus, vary over the business cycle. The adjustment costs of housing capital stem from the fixed supply of land so that the costs of new housing are convex in the produced quantity. The calibration and estimation of the model implies that adjustment costs for market capital are larger than those for residential capital (see Appendix B.6).

3 Estimation and Results

3.1 Calibration and Estimation

Calibration. Unless otherwise stated, my calibration follows DH and, thus, one period reflects one year. The assumptions on the adjustment cost function $\varphi(I_t/I_{t-1})$ ensure that these costs bear no influence on the model's balanced growth path. Since the relation between the degree of capital utilization and the rate of capital depreciation $\delta_k(u_{it})$ is not sector specific, the household will choose the same degree of capital utilization for all three kinds of capital usage in the long run. I normalize this long-run rate of capital utilization u to one. As a consequence, the model has the same balanced growth path as the model of DH.

The parameters of the household's current-period utility function u, the discount factor β, and the long-run rate of capital depreciation δ_k follow from the stationary solution of the model for exogenously given values of the interest rate, leisure, and the ratio of the capital stock and the stock of residential structures to GDP. The latter are determined from long-run averages.

The key parameters of the model are ϕ, φ'' and $\delta_k''u/\delta_k'$. For all of them, there is little guidance in the literature.

DH choose $\phi = 0.106$ as the share of land in the value of new houses. This value is from an unpublished memo of the Census Bureau. I use a different approach. The stationary solution of the model links the share of land in the value of new houses to the share of land in the value of existing houses (see the Appendix B.4 and DH). Davis and Heathcote (2007) present evidence that the latter share increased from 30-35 percent in 1985 to 40-45 percent in 2006 with an average of 36 percent. These results are in line with more recent explorations by Knoll et al. (2017). In order to match the observed land share in existing houses ($= 0.36$), I increase the DH value of ϕ to 0.2. Nevertheless, my robustness check presents results for $\phi = 0.106$.

Since I have no empirical long run counterparts for φ'' and $\delta_k''u/\delta_k'$, I estimate them together with the parameters of the shock process as I will describe in more detail below.

Table 1 presents both the calibrated parameter values as well as the several steady state values. Starred entries are computed from the model's stationary solution. Besides the capital depreciation rate and the land share in the value of new houses, all parameter values are not far from those of DH. The capital depreciation rate increases noticeably through the omitted capital income tax. Nevertheless, it is in a plausible range.

Table 1: Calibrated parameter values

Risk aversion: σ	2			
Discount factor: β	0.9688*			
k	C	H	N	
k's share in utility: μ_k	0.3*	0.04*	0.66*	
i	b	m	s	
Trend growth rates in i: g_{A_i}	-0.27%	3.1%	2.37%	
Capital share in i: θ_i	0.132	0.309	0.37	
j	c		d	
construction good share in j: B_j	0.031		0.47	
manufacturing good share in j: M_j	0.27		0.24	
service good share in j: S_j	0.7		0.29	
Land share in new houses: ϕ:	0.2			
Depreciation rate for houses: δ_h	0.0127**			
Capital depreciation $\delta_k(u_i)$	0.089*			
exogenous steady state values:	K/Y	P_hH/Y	$r-\delta_k(u_i)$	N
	1.52	1.56**	0.06	0.3

Notes: * endogenous by the model; ** based on the stock of residential structures S ($P_dS/Y = 1$ $\delta_s = 0.157$ from DH), Appendix B.4 provides more information.

Estimation. The detrended Solow residuals are equivalent to the technological shocks in the DH-model. In the present model, the Solow residuals reflect changes in the technology as well as unobservable changes in the rate of capital utilization. Adopting the DH approach would be misleading. I use a Bayesian full-information estimation to evaluate the parameter of the exogenous process, as well as the two remaining parameters φ'' and $\delta_k''u/\delta_k'$. To be in line with DH, I employ their Solow residuals as observables and add the following equations to the model

$$Solow_{it} = u_{it}^{\frac{\theta_i}{1-\theta_i}} z_{it} = \frac{X_{it}}{K_{it}^{\theta_i} N_{it}^{1-\theta_i}}^{\frac{1}{1-\theta_i}}. \tag{9}$$

The choice of prior distributions is presented in the columns 2-4 of Table 2 and plotted in Appendix Figure D.1. The parameter distributions of the exogenous processes are equal in all sectors and near the standard of the literature. The mean of the prior distribution of φ'' is the estimation value from Christiano et al. (2005) without habits in consumptions. To have a more diffuse prior, I double the amount of the standard error from their estimation for the standard deviation. The distribution for $\delta_k''u/\delta_k'$ is an inverse Gamma function with the mean and the standard deviation equal to one. The largest part of the mass is in the range of values often used in the literature.

Table 2: Prior and Posterior Distribution

	Prior distribution			Posterior distribution			
Parameter	Distribution	Mean	StD	5%	50%	95%	Mean
ρ_b	Beta	0.85	0.05	0.755	0.839	0.906	0.836
ρ_m	Beta	0.85	0.05	0.773	0.851	0.912	0.847
ρ_s	Beta	0.85	0.05	0.864	0.911	0.949	0.910
$100\sigma_{\epsilon,b}$	InvGamma	2	4	3.569	4.136	4.867	4.165
$100\sigma_{\epsilon,m}$	InvGamma	2	4	2.95	3.432	4.057	3.458
$100\sigma_{\epsilon,s}$	InvGamma	2	4	1.474	1.730	2.394	1.744
φ''	Gamma	0.91	0.36	0.349	0.764	1.438	0.812
$\delta_k''u/\delta_k'$	InvGamma	1	1	0.239	0.470	1.394	0.59

Notes: Draws from the posterior are approximated via RWMH with $\theta^i \sim N(\theta^{i-1}, \Sigma)$. Σ is the negative inverse of the Hessian at the mode of the posterior. I draw 250 000 times and burn the first 125 000.

The columns 5-8 of Table 2 presents the posterior distributions of the parameters. The autoregressive parameter in the construction sector is the smallest and in the service sector the largest one. The manufacturing autoregressive parameter is similar to the posterior distribution. The order of the autoregressive parameter means and the size of the means of ρ_m and ρ_s are very similar to the results from DH. The largest volatility of the innovations is in the construction sector and the lowest one in the service sector. The means of the parameters are very similar to the calibration from DH.[1] The median and the mean are very similar for each parameter of the exogenous processes. The distributions are not diffuse.

The distribution of the second derivative of the business investment adjustment costs function in the steady state, φ'', faces no noticeable changes due to the Bayesian update. The mean is 0.81, which is smaller than the mean of the prior.

The elasticity of $\delta_k'(u_{it})$ decreases markedly. The distribution is denser for small values and the mean is almost half of the prior.

The posteriors of ρ_b, ρ_m, and φ'' are similar to their priors. There are three possible reasons: a good choice of the prior, a weak identification, and the flatness of the likelihood function. A countercheck with more diffuse priors supports a strong identification:

[1]In an earlier version of the paper, I estimated three simple AR(1)-processes from the Solow residuals for the DH model. The results are similar to the presented exogenous parameters here.

Choosing jointly $\rho_i \sim U(0,1)$, the resulting posterior looks very similar (see Table D.3 of the Appendix). Furthermore, Figures D.2(a)-D.5(a) of the Appendix display joint posterior distributions of ρ_b with ρ_m as well as φ'' with ρ_b, ρ_m and $\delta_k'' u/\delta_k'$ and confirm that all posteriors are elliptical and by association regular so that the chosen algorithm performs well. I also plot in Figures D.2(b)-D.5(b) of the Appendix the shape of the likelihood function by choosing a uniform prior for the concerning parameters. It turns out that the likelihood function is flat in the dimension of φ'' and to some extent of $\delta'' u/\delta_k$.

To account for the posterior distribution and for problems that may occur in connection with the flat likelihood function, I check the robustness of the key moments for a broad range of the parameters φ'' and $\delta_k'' u/\delta_k'$.

3.2 Second Moments

Table 3 presents in column two second moments of U.S. data from 1969 to 2015. These moments confirm those of DH, except for the much larger volatility of house prices, which reflects the boom-bust during the first decade of the 2000s. The remaining columns of Table 3 are second moments implied by different versions of the model. They were computed from the first-order solution of the model and from the gain function of the HP-filter with weight 100 as proposed by Uhlig (1999), p. 48-49.[2]

The third column displays results from the model presented in Section 2. The fourth column presents second moments from the stripped-down DH model with the estimated independent technology shocks and with $\phi = 0.106$. Column five reports second moments from the DH model with their VAR(1)-process. In the interest of readability, I call my model "extended model", the stripped-down DH model with independent shocks "DH-AR model" and the DH model with correlated shocks "DH-VAR model".

The fluctuations of major economic activities are similar in all models. They capture that the standard deviation of residential investment is more than twice as large as of business investment. Output and hours worked are most volatile in the construction and less so in the service sector. Among the three models, the volatility of PCE in the extended model comes closest to the empirical value. The extended model predicts the largest relative standard deviation of house prices, which is still smaller than empirically observed. All models underestimate the volatility of hours worked and GDP and the extended one in

[2]In a former version of this paper, I used simulations of the second-order solution and computed second moments as averages of 1 000 simulations each with 250 periods. The results are almost identical.

particular.

All models predict the positive correlations between GDP, PCE, house prices, and business investment. Both the extended and the DH-VAR model match the positive co-movements between residential investment, GDP, PCE, and business investment, but cannot fully account for the empirically observed size of the correlation coefficients. The DH-AR model cannot reproduce these co-movements. Both versions of the DH model fail to mimic the positive correlation between house prices and residential investment. The extended model predicts the correct sign, but underestimates the empirically observed magnitude. The DH-AR model is unable to explain the positive correlation between output of the construction and the service sector. Overall, co-movements between the outputs on the intermediate stage of production are weak without correlated shocks.

GDP and business investment match the empirically observed lead-lag structure in the extended model. The cross-correlation between residential investment and lagged business investment is larger than their contemporaneous correlation. The DH-models predicts the reversed pattern. The extended model is in line with the empirical fact that the lead of residential investment over GDP is more pronounced than the lag of residential investment behind GDP. In the DH-AR model, this pattern is reversed. Nevertheless, the extended model is unable to predict the empirically observed lead of residential investment either over business investment or GDP. [3]

[3]The original model by DH (with government and population growth) reproduces a weaker correlation between the two investment types as well as a slightly negative correlation between residential investments and house prices. The cross-correlation between residential investment and GDP, where GDP is lagging is 0.05 points higher than in the case where residential investment is lagging. Further, in the DH-AR model with government and population growth, negative correlations are slightly stronger than in the stripped-down version.

Table 3: Simulated second moments

StD	USA 1969-2015			Extended model			DH-AR model			DH-VAR model		
GDP		2.00			1.29			1.38			1.81	
% StD to GDP												
PCE		0.96			0.80			0.59			0.58	
Hours worked		1.24			0.22			0.35			0.36	
Busi		2.51			2.01			3.08			2.92	
Resi		7.46			5.43			7.53			6.29	
House prices (p_h)		2.63*			0.80			0.54			0.44	
Output by sector	x_b	x_m	x_s	x_b	x_m	x_s	x_b	x_m	x_s	x_b	x_m	x_s
	3.75	1.93	1.18	3.82	1.87	1.10	4.39	1.81	1.12	3.50	1.52	0.95
Hours by sector	N_b	N_m	N_s	N_b	N_m	N_s	N_b	N_m	N_s	N_b	N_m	N_s
	2.92**	1.59**	0.78**	1.30	0.21	0.20	1.96	0.34	0.34	1.71	0.35	0.32
Correlations												
GDP, PCE		0.91			0.98			0.96			0.96	
p_h, GDP		0.66*			0.89			0.61			0.78	
PCE, Busi		0.57			0.78			0.87			0.88	
PCE, Resi		0.80			0.43			0.12			0.37	
Resi, Busi		0.40			0.28			0.01			0.32	
p_h, Resi		0.66*			0.19			-0.47			0.00	
Output by sector	x_b, x_m	x_b, x_s	x_m, x_s	x_b, x_m	x_b, x_s	x_m, x_s	x_b, x_m	x_b, x_s	x_m, x_s	x_b, x_m	x_b, x_s	x_m, x_s
	0.72	0.72	0.9	0.16	0.12	0.16	0.12	0.01	0.24	0.25	0.34	0.69
Hours by sector	N_b, N_m	N_b, N_s	N_m, N_s	N_b, N_m	N_b, N_s	N_m, N_s	N_b, N_m	N_b, N_s	N_m, N_s	N_b, N_m	N_b, N_s	N_m, N_s
	0.79**	0.90**	0.82**	0.52	0.27	0.96	0.36	0.11	0.97	0.59	0.41	0.98
Lead-lag correlations	i=1	i=0	i=-1	i=1	i=0	i=-1	i=1	i=0	i=-1	i=1	i=0	i=-1
Busi_{t-i}, GDP_t	0.22	0.77	0.59	0.41	0.88	0.81	0.54	0.94	0.29	0.54	0.96	0.33
Resi_{t-i}, GDP_t	0.78	0.75	0.15	0.28	0.49	0.13	0.06	0.23	0.23	0.23	0.48	0.25
Busi_{t-i}, Resi_t	-0.09	0.41	0.65	0.01	0.28	0.31	0.12	0.01	-0.06	0.20	0.32	0.11

Notes: Empirical second moments are from per capita logged HP-filtered annual data (weight=100). Appendix A provides a detailed overview. * only available since 1970; ** only available for 1969-2000 due to changes in survey methodology in 2000, Table D.1 in Appendix D provides additionally data from 2000 onwards. Second moments from the various versions of the model are analytical moments based on the first-order solution of the model and the gain function of the HP-filter with weight 100 (see Uhlig (1999)).

3.3 Robustness and Discussion

This section gives insights in the model's mechanics and the contribution of each of the extensions to the model's results by adding the extensions one by one to the DH-model and by presenting the sensitivity of key correlations with respect to the parameters ϕ, φ'' and $\delta_k''u/\delta_k'$. Finally, I will present the results of a re-estimated model that combines my extension with the VAR(1)-shock-process assumption.

Table 4 presents second moments from several AR(1) models. I will refer to them as A1 and A through E so that column headings and model names coincide. Column A1 refers to the DH-AR model. For the readers' convenience, it repeats results already presented in Table 3. Column A refers to my model without any of its amendments except the increase to $\phi = 0.2$ from $\phi = 0.106$. Model B adds adjustment costs of business capital to model A, model C is model B with limited capital mobility, and model D is the extended model from Section 2. Finally, model E is model D but with a variable utilization rate of housing u_h. The elasticity of $\delta_h'(u_h)$ with respect to u_h is set to zero.[4]

Figure 2 presents the effects of the three parameters ϕ, φ'', and $\delta_k''u/\delta_k'$ on key correlations.

Table 5 presents second moments from VAR(1) models. I will refer to them as D, V1 and F. Model D is the extended model again and V1 the DH-VAR model. Both repeat results already presented in Table 3. The results in column F refer to my model, re-estimated under the assumption of a VAR(1)-shock-process. The re-estimation includes φ'' and $\delta_k''u/\delta_k'$. The Appendix Section B.4 explains the estimation strategy, Table D.4 outlines the priors, and Table D.5 presents information about the posteriors.

Co-movement. Consider, first, the driving forces of co-movements between sectoral outputs. A positive sectoral shock triggers two effects: a substitution effect, because the price of the affected good decreases and an income effect, because the output for a given amount of inputs increases. Under the assumption of normal goods, the output of all sectors will increase if the income effect dominates the substitution effect. This is, among others, the case, if the cost shares of an input factor in the production of final goods are similar.

Consider, second, the correlation between final goods and their prices. Here, too, income and substitution effects are at work. Prices and quantities will move together, if the cost

[4]The case of a fixed utilization rate is equivalent to the case $\delta_h''u_h/\delta_h' = \infty$. Therefore, $\delta_h''u_h/\delta_h' = 0$ marks the opposite pole of the possible range of values.

Table 4: Robustness AR(1): selected second moments

Moments	Data	A1	A	B	C	D	E
% StD to GDP							
Busi	2.51	3.08	3.11	1.79	1.80	2.01	2.01
Resi	7.46	7.91	4.79	5.99	5.77	5.43	5.72
p_h	2.63	0.54	0.52	0.82	0.82	0.80	0.82
Corr(Resi$_t$,x$_t$)							
x=Busi	0.40	0.01	0.12	0.26	0.27	0.28	0.30
x=GDP	0.75	0.23	0.26	0.45	0.45	0.49	0.51
x=PCE	0.80	0.12	0.19	0.36	0.36	0.43	0.43
x=p$_h$	0.66	−0.47	−0.18	0.08	0.09	0.19	0.28
Lead-Lag-Pattern: Corr((x$_{t-1}$,y$_t$)−Corr(x$_{t+1}$,y$_t$))							
x=Busi,y=GDP	−0.37	0.25	0.23	−0.33	−0.32	−0.40	−0.37
x=Resi,y=GDP	0.63	−0.17	−0.15	0.12	0.10	0.15	0.13
x=Busi,y=Resi	−0.74	0.16	0.19	−0.23	−0.22	−0.30	−0.30

Notes: column labels:

A1: DH-AR model,

A: AR(1) model and ϕ=0.2,

B: model A and investment adjustment costs,

C: model B and limited capital mobility,

D: model C and variable capacity utilization,

E: model D and variable utilization of housing for $\delta_h'' u_h/\delta_h' = 0$;

Empirical second moments are from HP-filtered annual data (weight=100). Second moments from the various versions of the model are analytical moments based on the first-order solution of the model and the gain function of the HP-filter with weight 100 (see Uhlig (1999)).

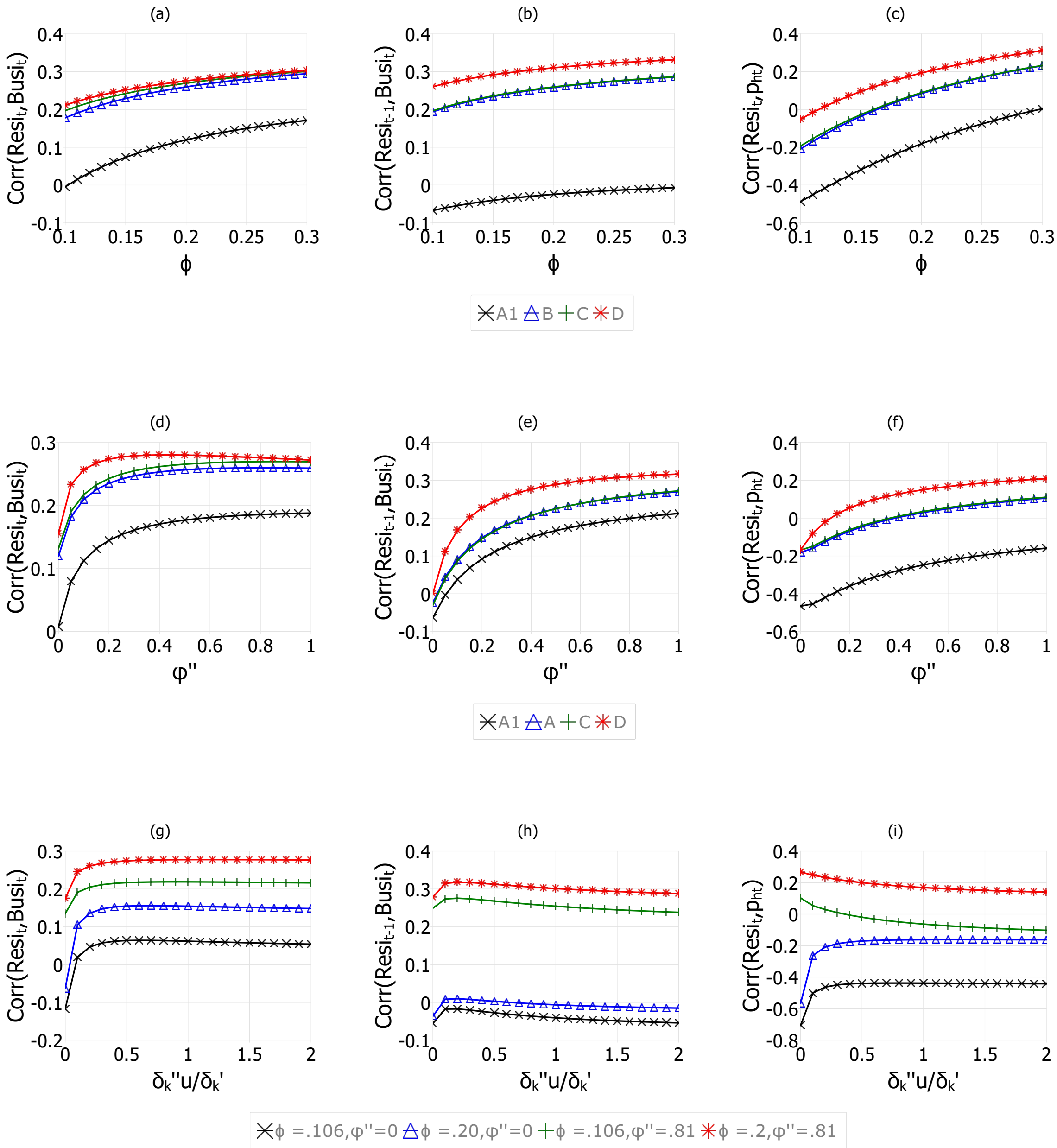
share of the affected input in the production of the final good is small and if the income effect of the shock dominates the substitution effect.

Consider, in particular, the correlation between house prices and residential investment. In the Appendix B.2, I derive the covariance of the cyclical component of house prices $\hat{p}_{ht}$ and residential investment $\hat{y}_{dt}$. It is given by

$$\text{cov}(\hat{p}_{ht}, \hat{y}_{dt}) = \text{cov}(\hat{p}_{dt}, \hat{y}_{dt}) + \phi\ \text{var}(\hat{y}_{dt}). \tag{10}$$

Since the shocks in the construction sector are large and the cost share of construction in the production of residential investment is high, there is a large negative covariance between the price and the quantity of residential investment cov($\hat{p}_{dt}, \hat{y}_{dt}$). Furthermore, since ϕ is markedly smaller than one, equation (10) implies a negative correlation between

Figure 2: Robustness Analysis (Parameter Sensitivity)



house prices and residential investment in the DH-AR model. Iacoviello and Neri (2010) argue similarly.

Adjustment costs of new houses. Column A of Table 4 documents the effects of the cost share of land in the production of houses ϕ.

Compared to the DH-AR model, the higher land share lowers the volatility of residential investment by 40 percent and increases the volatility of business investment slightly. All contemporaneous correlation coefficients related to residential investment increase and tend towards the empirical observations. The correlation with house prices is still negative.

Panels (a)-(c) of Figure 2 illustrate the effects of the parameter ϕ in further detail. The correlation between business and residential investment increases with the cost share of land in all models. There is, however, a sizable effect of the adjustment costs of business investment represented by the vertical distance between the respective lines in Panel (a). Panel (b) shows that the A1 model is not able to generate a possible correlation between lagged residential and contemporary business investment for reasonable values of ϕ. Adjustment costs of business investment markedly increase this correlation and variable capacity utilization enhances this effect. Panel (c) shows a similar picture with respect to the correlation between residential investment and house prices. Even though the cost share of land markedly increases this correlation in the A1 model, this model alone is not able to generate a positive correlation. It is the combined effect of adjustment costs of business investment, variable capacity utilization, and a sufficiently large share of land that accomplishes this result. The starred lines at $\phi = 0.1$ show that my model with the land share employed by DH is almost as successful as the DH-VAR model; both predict a positive correlation between the investment types and a correlation near zero between residential investment and house prices.

The results of Chang (2000) provide the reasoning. He shows in a model with different kinds of investment that adjustment costs decrease the volatility of the affected variable and increase the co-movement of the other ones. The reason in the field of housing is, with a higher land share an additional unit of housing becomes more costly. The price elasticity of demand reduces and thereby the substitution effect is also lowered. This reduction also weakens the negative covariance between the price and the quantity of residential investment; the first term of the right-hand side of equation (10). The second term of the right-hand side depicts the direct positive effect of a larger land share on the covariance between house prices and residential investment.

Adjustment costs in business investment. Column B in Table 4 displays the effects of business investment adjustment costs and vertical distances between the respective lines in Figure 2 provide further information.

Adjustment costs lower the volatility of business investment by more than one third and increase the volatility of residential investment. The volatility of house prices increases by over 50 percent. All correlation coefficients related to residential investment increase and are positive. The lead-lag pattern tends towards the data. Panels (d)-(f) of Figure 2 show that the key moments are robust for φ''>0.5; in the extended model even for smaller values of φ''.[5] Overall, Figure 2 illustrates that adjustment costs are the most important extension. Its effects are the largest and they are a prerequisite for the positive effects of variable capital utilization.

The introduction of CEE adjustment costs has three effects. The first one is related to the finding of Chang (2000). The volatility of business investment decreases and co-movements with residential investment increases. The second effect rests on the broader usability of business investment and drives the lead of business investment over residential investment in the DH-AR model. Kydland et al. (2016) argue that a positive technology shock initially increases business investment and as a result productive capital. The resulting higher output in the following periods is used for more consumption and residential investment. Adjustment costs diminish the benefits of this strategy. They thereby reduce the lead of business investment over residential investment and improve the co-movement between both kinds of investment. The third effect rests on the kind of adjustment costs. CEE adjustment costs depend on the previous amount of investment. A smooth humped-shaped adjustment of investment is optimal so that business investment lags other economic activity. Since business investment is a sizable fraction of GDP, the business cycle shifts slightly. The lead-lag pattern of GDP and residential investment moves slightly toward the empirically observed pattern.

Limited capital mobility. The difference between columns C and B in Table 4 displays the effect of limited capital mobility. The changes are marginal. Figure 2 corroborates this finding: the vertical distances between the lines marked with triangles and those marked with crosses in Panel (a)-(f) are small and very often invisible. The small effects decrease even further with the introduction of variable capital utilization, which acts as a substitute of limited sectoral mobility of capital. This result is in contrast to Iacoviello and Neri (2010), where limited capital mobility enhances the co-movement between different

[5] I also checked the robustness for $\varphi'' \in [1, 2]$ to account for the posterior distribution. Changes are negligible.

investment types markedly.

Variable capital utilization. Column D in Table 4 displays the effects of introducing variable capital utilization. In Figure 2, the vertical distances between the lines marked with crosses and those marked with stars in Panel (a)-(f) provide further information on these effects. Variable capital utilization improves the lead-lag pattern and the correlation of residential investment with house prices, PCE, and GDP. Panels (d)-(f) of Figure 2 indicate that in the range of small adjustment costs of business investment – approximately in the interval $\varphi'' \in [0, 0.4]$ – variable capital utilization has a sizable positive effect on the correlations so that the robustness of model with respect to the choice of φ'' increases. Panels (g)-(i) illustrate the effects of the parameter $\delta_k'' u/\delta_k'$ on the key correlation coefficients. Except for small values, the effects are limited so that the model is largely robust with respect to the choice of this parameter. Without business investment adjustment costs, $\varphi'' = 0$, a small elasticity of δ_k' has a negative effect on the correlation between residential investment and house prices, which changes sign when adjustment costs are included. This change takes place at $\varphi'' \approx 0.18$. Without adjustment costs, the effects of variable utilization are minor.

The rate of capital utilization is an increasing function of the value of the marginal product of capital. A higher demand increases prices and so does the value of the marginal product. A positive sectoral shock also increases the sectoral value of the marginal product. Provided that the income effect dominates, each sectoral shock increases the value of the marginal product of capital in all sectors and thus the capital utilization rates and sectoral quantities. This mechanism reinforces the income effect. If the substitution effect dominates, the income effect is not reinforced. This phenomenon explains the requirement of adjustment costs.

CEE adjustment costs interact in a second way with variable capital utilization rates. Current increases in business investment lower the costs of replacing capital because higher investments are less costly in the next period and so a higher capital utilization ensues. The depreciation rates increase and thereby so too does the demand on business investment, therefore increasing the volatility and the lag of such investment.

Variable housing utilization. One could argue that the utilization of housing is also variable. To admit this point of view, I introduce a variable rate of depreciation of houses into model D. Column E of Table 4 presents the results for this model. As in the case of business capital, the rate of depreciation is an increasing function of the utilization of the home: $\delta_h(u_h)$. I choose the lowest possible elasticity of the first derivative of the deprecation rate to demonstrate the most extreme case ($\delta_h'' u_h / \delta_h' = 0$). Besides the correlation of house prices and residential investment, which increase slightly, the effects are marginal.

Table 5: Robustness VAR(1): selected second moments

Moments	Data	D	V1	F
% StD to GDP				
Busi	2.51	2.01	2.92	1.86
Resi	7.46	5.43	6.29	4.89
p_h	2.63	0.80	0.44	0.74
Corr(Resi$_t$,x$_t$)				
x=Busi	0.40	0.28	0.32	0.44
x=GDP	0.75	0.49	0.48	0.72
x=PCE	0.80	0.43	0.37	0.72
x=p$_h$	0.66	0.19	0.00	0.57
Lead-Lag-Pattern: Corr((x$_{t-1}$,y$_t$)−Corr(x$_{t+1}$,y$_t$))				
x=Busi,y=GDP	−0.37	−0.40	0.21	−0.42
x=Resi,y=GDP	0.63	0.15	−0.02	0.28
x=Busi,y=Resi	−0.74	−0.30	0.09	−0.53

Notes: column labels:

D: extended model,

V1: DH-VAR model,

F: VAR(1)-shocks, $\phi = 0.2$, investment adjustment costs, variable capacity utilization, and limited capital mobility.

Empirical second moments are from HP-filtered annual data (weight=100). Second moments from the various versions of the model are analytical moments based on the first-order solution of the model and the gain function of the HP-filter with weight 100 (see Uhlig (1999)).

Var(1)-Process. Column F of Table 5 presents second moments from an extended estimated DH-VAR model. The estimation includes the parameters φ'' and $\delta_k'' u / \delta_k'$. Appendix B.4 provides information regarding the chosen priors and the resulting posteriors. The relative standard deviations of residential and business investment decrease in Model F and depart slightly more from the empirical observations. The volatility of house prices increases compared to model V1 but decreases slightly compared to model D, and is still smaller than empirically observed. Model F matches the empirically observed contemporaneous correlations well. Compared to both the DH and the V1 model the correlations increase and move close to the values found in the data. Model F also comes closer to the empirical lead-lag-pattern but still underestimates the lead of residential investment.

The lower volatilities of both investment types are due to adjustment costs. The estimated standard deviations of the innovations are similar to the DH-VAR ones. Thus, including adjustment costs reduces the volatility of investment. Correlated innovations induce stronger co-movements. Correlated innovations may be seen as a nesting of aggregate and sector-specific innovations, as illustrated by an example in Appendix C. The former decrease the substitution effect and strengthen the income effect. The better fit of the cross-correlation of residential investment with GDP relies on the whole VAR(1)-shock-process and the better fit of the cross-correlation of residential with business investment relies only on the correlated innovations. The effect of a slightly higher estimate for φ'' is minor.[6] Despite of the increased performance of Model F, the gain of knowledge is limited, because the sources of this success are the properties of technological shocks on which the model does not shed light.

4 Conclusion

This paper explores the role of uncorrelated sector-specific technology shocks to induce aggregate economic fluctuations being in line with a number of well-established stylized facts. The facts reported in DH and echoed by several other papers include (i) the co-movements of GDP, PCE, business and residential investment, and house prices, (ii) the fact that residential investment is more than twice as volatile as business investment, and (iii) that business investment lags GDP, but residential investment leads GDP.

DH present a multisectoral model with correlated shocks to sectoral labor augmenting technical progress, which is able to explain fact (ii) and mostly (i) but fails to be in line with fact (iii). This model with uncorrelated shocks is unable to generate co-movements in housing or rather in residential investment and the remaining economic activity. Hence, fact (i) is mostly driven by the shock's correlation. I introduce two frictions in the form of adjustment costs of business investment as in Christiano et al. (2005) and limited sectoral mobility of capital as in Boldrin et al. (2001) into their model and increase the adjustment costs to new houses. Furthermore, I introduce variable capacity utilization as in Jaimovich

[6] I checked this by setting φ'' to the AR(1) estimate, the off-diagonals of the autoregressive and of the covariance-variance matrix to zero, respectively.

and Rebelo (2009). The extended model is able to replicate facts (i) and (ii). The model accounts partly for (iii) since business investment lags residential investment and GDP. The main improvement in the empirical plausibility of the model is due to adjustment costs the effect of which is enhanced and becomes more robust by capacity utilization. The effect of sectoral immobility is small. The results are robust even for small adjustment costs ($\varphi'' > 0.3$).

Several versions of the model demonstrate its robustness. The extended model with the DH's amount of adjustment costs to new houses is similarly successful as the DH-VAR model, VAR(1) shocks improves the performance of the extended model, and variable housing utilization has a positive effect on the correlation between residential investment and house prices with minor effects on other second moments.

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