A Real Explanation for Heterogeneous Investment Dynamics

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Abstract

Household investment, that is investment in consumer durables and housing, leads non-residential fixed investment over the U.S. business cycle. This observation represents a potent challenge to real business cycle (RBC) theory. First of all the theory has been unable to account for it. In addition, research suggests the observation is driven by monetary shocks, supporting the view that these shocks play a leading role in the U.S. business cycle. This paper shows that RBC theory is consistent with the investment dynamics after all. It does so by generalizing the standard home production environment to take into account the fact that household capital is useful in market production.

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1. Introduction

Since the work of Burns and Mitchell (1946) it has been recognized that business fixed investment and household investment in residential capital and consumer durables behave differently over the business cycle: household investment leads business investment over the business cycle. This phenomenon has prevailed throughout the post-WWII period. As illustrated in Figure 1, around most of the nine post-war recessions, household investment reaches its peak and then its trough before business investment.

This evidence represents a potent challenge to real business cycle (RBC) theory. First of all the theory has been unable to account for the investment dynamics. The most success these models have achieved is to account for the fact that the two kinds of investment co-move positively over the cycle. Indeed the literature is replete with papers which have succeeded with respect to the comovement phenomenon but failed with respect to the dynamics.[1] In addition, both empirical and theoretical research suggests that the observation is driven by monetary shocks.[2] When combined with the failure of RBC theory this research supports the view that monetary and not real shocks play the leading role in the U.S. business cycle.

This paper shows that RBC theory is consistent with the investment dynamics after all. It does so by generalizing the home production framework typically used to analyze these dynamics. The generalization introduced is motivated by the idea that the effectiveness of hours worked in the market is positively related to the quantity and quality of household capital. For example, analogous to the maintenance required to keep business capital in operating condition, the quality of market labor hours is improved by activities at home such as rest, relaxation, and personal care. Another example is the role of automobiles in commuting, a crucial input into market production. These observations suggest that household

[1] I believe a complete list of RBC studies which have examined the behavior of home and business investment in closed economies includes: Baxter (1996), Benhabib, Rogerson and Wright (1991), Campbell and Ludvigson (1998), Chang (2000), Einarsson and Marquis (1997), Fisher (1994, 1997), Gomme, Kydland and Rupert (2000), Greenwood and Hercowitz (1991), Greenwood, Rogerson and Wright (1995), Hornstein and Praschnik (1997), McGrattan, Rogerson and Wright (1997), and Perli (1998).

[2] Papers providing empirical support for the view that monetary factors can generate the heterogeneous investment dynamics include Bernanke and Gertler (1995) and Fisher (1994). Two recent papers in which the dynamics arise out of general equilbrium models of money are Edge (2000) and Li and Chang (2001).

capital should be modeled as a complement to time in the supply of effective hours used to produced market goods. Despite this seemingly obvious feature of household capital, the standard home production model assumes that household capital has no use in market production.[3]

The generalized home production framework can account for the investment dynamics because it reverses a basic asymmetry in the treatment of capital goods in the standard home production model. In the standard model business capital is useful in the production of market consumption and business and household investment goods. Crucially, it is useful for producing new household capital goods which are an input into home produced consumption goods, while household capital has only one purpose as an input into home produced consumption goods. This asymmetry implies a strong incentive to build up business capital before household capital in response to a positive innovation in market productivity. If household capital has some use in market production then this asymmetry is reversed since household capital is useful in producing both market and home produced goods, while business capital can only be used to produce market goods.

I analyze the generalized home production formulation in the context of alternative assumptions on technologies for producing new investment goods. These assumptions are motivated by the work of Topel and Rosen (1988) and the empirical studies summarized by Kydland and Prescott (1982) and Christiano and Todd (1996). In particular the short run elasticity of household investment is much greater than for business investment, in response to aggregate disturbances. As well, there is plenty of evidence justifying this difference in elasticities. There are significant gestation lags in new non-residential fixed investment projects as well as a significant period of planning which takes time but requires relatively few resources. These observations justify incorporating into the home production framework differences in the way investment is undertaken across household and business capital, with longer planning and gestation lags for the latter. Realistic gestation and planning lags reinforce the incentives to build up household capital in advance of business capital in the generalized home production framework.[4]

[3]The standard calibration procedure for a single-capital-good RBC model involves aggregating household and business capital to arrive at a single capital stock measure. Implicit in this practice is the assumption that household capital is useful in producing market goods and in particular is perfectly substitutable with business capital. The current analysis involves household and business capital being less than perfect substitutes.

[4]It should be noted that the notion of gestation lags being important for understanding the heterogeneous investment dynamics has a long tradition in macroeconomics and is even enshrined in macroeconomics textbooks. See for example, Hall and Taylor (1997).

I show that the general home production formulation can reconcile RBC models with the observed lead-lag pattern between household and business investment, but gestation lags and planning differences across types of investment in the context of standard home production models cannot. Moreover, the general home production framework can account for the fact that household investment is more volatile than business investment. The standard home production models studied here, even with realistic gestation and planning lags in market investment, consistently predict the opposite.

In a recent paper Gomme, Kydland and Rupert (2001) study gestation lags in the context of standard home production models. They conclude that these lags can move the standard home production framework into substantial conformity with the data in terms of the observed investment dynamics. One contribution of this paper is to show that the results underlying this conclusion are fragile and that once new data is incorporated into the analysis, particularly new capital stock data, they no longer hold. That is, gestation lags cannot account for the data unless they are included in a model of home production of the general form introduced in this paper.

The rest of the paper proceeds as follows. In the next section I describe the model. After this I describe how I selected parameter values. This is followed by a discussion of the findings. The final section concludes and suggests avenues for future research.

2. The Model

The model consists of households, firms and a government acting in a competitive equilibrium. It departs from the standard home production model in two ways. First, household capital is assumed to be complementary with labor and business capital in market production. Second, there can be differences across household capital and business capital in terms of the time required for planning and completing new investment projects.

2.1. Households

The representative household has preferences over a consumption good purchased from firms, c_{mt}, a consumption good produced in the home, c_{ht}, hours devoted to home production, n_{ht} and hours sold in the labor market, n_{mt}. These preferences are given by

$$\mathcal{E}_t \sum_{j=t}^{\infty} \beta^{j-t} \left[\ln c_{mj} + \psi \ln c_{hj} + \eta \ln \left(1 - n_{mj} - n_{hj}\right) \right], \tag{2.1}$$

where $\mathcal{E}_t$ is the mathematical expectations operator conditional on time t information and $\eta, \psi > 0$. This particular specification of preferences is chosen because it can reconcile the trend in the price of household investment goods in terms of non-durable and service consumption and the stable nominal share of expenditures on household investment goods observed in U.S. data. Assuming less or more substitution between home and market consumption would not be consistent with this evidence (see Fisher 1994, 1997 and Kydland 1995). Aside from its use in pinning down preferences, the relative price trend plays no direct role in the analysis. This helps maintain comparability with previous studies.

The key difference with standard home production models is in the nature of labor hours supplied to the market. I assume that household's are compensated by firms for *effective* hours, $\widetilde{n}_{mt}$, where effective hours are derived from inputs of market time and household capital. Specifically,

$$\widetilde{n}_{mt} \leq h_{mt}^{\mu} (z_t n_{mt})^{1-\mu}, \tag{2.2}$$

where z_t is the level of labor-augmenting technology, h_{mt} is the stock of household capital devoted to maintaining and enhancing the quality of market hours, and $0 \leq \mu < 1$. As described in the introduction, the essential idea here is that the effectiveness of hours worked in the market is enhanced by the quality and quantity of household capital used in activities at home and in commuting to work. In general it is reasonable to suppose that both household capital and non-market time are inputs into producing effective market hours. I assume that only the former is used to make the model easily comparable to standard home production models.

At each date t the household faces the following budget constraint

$$c_{mt} + x_{mt} + x_{ht} \leq (1 - \tau_k) r_t k_t + (1 - \tau_n) w_t \widetilde{n}_{mt} + \delta_m \tau_k k_t + \xi_t. \tag{2.3}$$

Here x_{mt} is the household's investment in business capital, x_{ht} is investment in household capital, k_t is the household's stock of business capital, r_t is the rental rate on that capital and w_t is the wage for effective hours worked. Business capital and effective market hours are taxed at the rates τ_k and τ_n, respectively. Consistent with the U.S. tax code, there is a depreciation allowance for capital taxation, $\delta_m \tau_k k_t$, where $0 < \delta_m < 1$ is the rate of depreciation on business capital. Notice that since household capital contributes to effective market hours it is subject to the labor tax. Finally, ξ_t is a lump-sum transfer from the government.

Throughout the analysis, I assume that household capital projects take one period to complete. That is, the stock of household capital, h_t accumulates according to

$$h_{t+1} = (1 - \delta_h) h_t + x_{ht}. \tag{2.4}$$

In addition to being an input into effective market hours, household capital is an input in the production of home goods. Specifically,

$$c_{ht} \leq h_{ht}^{\phi} \left(z_t n_{ht} \right)^{1-\phi}, \tag{2.5}$$

where h_{ht} is the amount of household capital devoted to home production and $0 < \phi < 1$. As in Greenwood and Hercowitz (1991) the level of labor-augmenting technology is identical in home and market production. However, as these authors emphasize, given the specification of preferences in (2.1), variation in z_t will have no impact on equilibrium outcomes through home production. Its inclusion here is merely to facilitate balanced growth. Finally, in any given period the uses of household capital in enhancing effective market hours and in producing home goods are subject to the availability of household capital in that period. Hence,

$$h_{ht} + h_{mt} \leq h_t. \tag{2.6}$$

Business capital is accumulated according to the technology considered by Kydland and Prescott (1982). Specifically, business capital projects require a flow of investment lasting J periods until they are completed. Let s_{jt} denote the number of projects j periods from completion at time t and let ω_j denote flow of investment in a project j periods from completion. Then, total business investment at date t is

$$x_{mt} = \sum_{j=1}^{J} \omega_j s_{jt} \tag{2.7}$$

and projects evolve according to

$$s_{jt+1} \leq s_{j+1t}, \tag{2.8}$$

$j = 1, 2, \ldots, J-1$. Given this structure, business capital accumulates as follows

$$k_{t+1} = (1 - \delta_k) k_t + s_{1t}. \tag{2.9}$$

The problem of the representative household is: maximize (2.1) subject to (2.2)-(2.6) by choice of c_{mt}, c_{ht}, h_{t+1}, k_{t+1}, s_{1t+1}, s_{2t+1}, ..., s_{J-1t+1}, s_{Jt}, h_{mt}, h_{ht}, n_{mt} and n_{ht}.

2.2. Firms

Firms produce a single output good, y_t, which can be used as market consumption as well as both kinds of investment. They choose business capital and effective labor services to maximize profits,

$$y_t - r_t k_t - w_t \widetilde{n}_{mt},$$

where

$$y_t \leq k_t^{\alpha} \widetilde{n}_{mt}^{1-\alpha}.$$

Recall from (2.2) that effective market hours, $\widetilde{n}_{mt}$, are influenced by the level of labor augmenting technical change, z_t. As is standard, I assume this grows at the deterministic gross rate $\gamma \geq 1$ and is subject to exogenous disturbances:

$$z_t = \gamma^t \exp(\theta_t), \;\; \theta_t = \rho\theta_{t-1} + \varepsilon_t, \;\; \varepsilon_t \sim \mathbf{N}(0, \sigma^2).$$

2.3. Government

Government is included in the model to make the analysis comparable to the literature. Its only function in the model is to raise revenues and rebate these revenues lump-sum to households:

$$\xi_t = \tau_k r_t k_t + \tau_n w_t \widetilde{n}_{mt} - \delta_k \tau_k k_t.$$

3. Parameter Selection

In order to implement the model I must select values for the following parameters:

$$\beta, \psi, \eta, \phi, \mu, \delta_h, \delta_k, J, \{\omega_i : i = 1, 2, ..., J\}, \alpha, \gamma, \rho, \sigma, \tau_k, \tau_n.$$

The strategy I use for doing this closely follows the one outlined in Greenwood, Rogerson and Wright (1995) which is also implemented by Gomme, *et. al.* (2001). The main difference with the calibration procedure used in these studies is the data underlying the parameter choices. In particular, the new capital stock estimates used here imply noticeable changes to long-run averages which are an important input into the calibration procedure. As is outlined in the following section, these changes have a significant impact on inference.

I analyze six versions of the model, which differ in terms of their assumptions on the market investment technology and the use of household capital in determining effective market hours. Conditional on the parameters underlying these differences, the remaining parameters are either identical or chosen in a consistent manner across versions of the model. The parameter values corresponding to the six versions of the model considered are summarized in Table 1. I now explain how these parameter values were chosen.

Common across the different models are the time discount factor, the two tax rates and the process governing labor-augmenting technology. The discount factor β is set so that a period in the model is a quarter of a year and the real interest rate is 6 percent at an annual rate along a non-stochastic balanced growth path. The tax rates are the values used by Greenwood, *et. al.* (1995), $\tau_n = 0.25$ and $\tau_k = 0.7$. The value for the labor tax is close to values used elsewhere in the RBC literature. Greenwood, *et. al.* (1995) use the relatively large value of the capital tax rate because without it the home production framework cannot simultaneously account for observed capital output ratios and labor's share of national income. In addition they defend the value as being reasonable because it is the mean of reported values in Feldstein, Dicks-Mireaux and Poterba (1983) and because it captures "all forms of government regulation, interference, or any other institutional disincentive to invest in business capital, not only direct taxation (p.165)." As in Greenwood, *et. al.* (1995) I choose the growth rate of labor-augmenting technology, γ, using the growth rate of per-capita GDP (excluding housing services) over the sample period of this study, 1948-1999. The remaining parameters for the technology process are chosen to be consistent with other papers in the literature: $\rho = 0.95$ and σ is set so that the innovation of $\exp((1-\alpha)(1-\mu)\theta_t)$ has a standard deviation of 0.00763.[5]

I consider three versions of the market investment technology. The first corresponds to the technology which is the mainstay of the RBC literature, the one-period time-to-build case. This involves setting $J = 1$ and $\omega_1 = 1$. The second is the case considered by Kydland and Prescott (1982) and Gomme, *et. al.* (2000). This is the four quarter time-to-build formulation and involves setting $J = 4$ and $\omega_1 = \omega_2 = \omega_3 = \omega_4 = 0.25$. This captures the fact that business capital projects generally take longer than household capital projects to complete. The third case is motivated by Christiano and Todd (1996). They discuss evidence on both the planning and building of new investment projects and argue that in the early phase

[5]The Solow residual computed from the models considered in this paper will not in general be identical to ones arising from a single-capital-good RBC model. In principle this suggests an adjustment to the assumed technology process is in order. However, since capital does not vary much over short horizons in the model, the differences with other models are very small so that modifications to the technology process are unnecessary to retain consistency with previous studies.

of many non-residential fixed investment projects relatively few resources are consumed. Instead, time is spent drawing up plans, gaining regulatory approval and in other relatively low resource cost tasks. These "time-to-plan" considerations are more relevant for business investment than household investment, and are at least as empirically justified as Kydland and Prescott's (1982) original time-to-build formulation.[6] Following Christiano and Todd (1996) I model time-to-plan by keeping the four-period time-to-build formulation and assuming the resource cost in the first period of a market investment are lower than in the last three periods. Specifically I set $J = 4$, $\omega_4 = 0.1$ and $\omega_1 = \omega_2 = \omega_3 = 0.3$.

The preference parameters ψ and η, the home production parameters ϕ and δ_h, and the market production parameters α and δ_k are chosen using the exact procedure described by Greenwood, *et. al.* (1995). Specifically, conditional on the other parameter values, these parameters are chosen so that along the non-stochastic balanced growth path, the model matches six calibration targets: the fractions of time devoted to market and non-market work, the ratios of market and household capital to output, and the shares in real output of market investment and household investment. The first two targets are taken from the same time-use studies discussed by Greenwood, *et. al.* (1995): 1/3 of the time endowment is devoted to market work and 1/4 to non-market work. The other four targets are based on the most recently available data on capital stocks, investment and output. Business capital is measured as private non-residential fixed capital and household capital is measured as the chain-weighted sum of the stock of private residential capital and consumer durables. The two investment series are measured analogously and output is measured as GDP less consumption of housing services. All variables are measured in chained 1996 dollars.

As describe in Katz and Herman (1997), the Bureau of Economic Analysis has revised its methodology for computing capital stock and investment series. In addition to incorporating the new chain-weighting methodology, the biggest change is in the way depreciation is calculated. Depreciation is now calculated geometrically instead of in the straight-line way used before, and data on secondary capital markets is used to estimate appropriate rates of depreciation. An outcome of using the revised methodology is that in many cases depreciation estimates have been substantially reduced and consequently estimates of capital stocks are, overall, much larger than previously estimated.[7] For investment, another change is that

[6]See Edge (2000) for a discussion of the empirical evidence showing significant differences in gestation lags and planning periods for residential and non-residential structures.

[7]For example, Katz and Herman (1997, p. 75, Table C) report that the total net stock of

software is now included in the measure of private non-residential fixed capital. This also has the effect of increasing the market capital stock.

These changes in methodology have a substantial impact on estimates of capital-output ratios. Using the sample period 1948-1999, I estimate the mean market capital:output ratio to be 4.79 and the mean household capital:output ratio to be 5.77. Greenwood, *et. al.* (1995) report mean values for these ratios of 4.00 and 5.00, respectively.[8] The investment shares are changed by less. These are now 0.094 and 0.116 for business investment and household investment, respectively, compared to the values of 0.118 and 0.135 used by Greenwood, *et. al.* (1995). As is described in the next section, these new estimates have a substantial impact on inference in home production models.

It remains to describe how I select the share of household capital in producing effective market hours, μ. I consider two cases for μ. One case corresponds to the standard formulation of home production in which household capital is not useful in market production at all. This involves setting $\mu = 0$. I refer to versions of the model with this parameter choice as *pure* home production models. The other case incorporates the notion of household capital being useful in market production and is referred to as *general* home production.

In the absence of independent evidence on μ, I select μ to demonstrate the potential for general home production models to account for the observed investment dynamics. To this end, for each of the general home production models studied, μ is chosen by minimizing a measure of the distance between the model and empirical dynamic correlations between detrended log household and business investment. Let $\Psi(\mu)$ denote the mapping from μ to the model correlations between x_{ht+j} and x_{mt}, $j = -2, -2, 0, 1, 2$, and let $\widehat{\Psi}$ denote the corresponding empirical estimates. My estimator for μ is the solution to

$$\min_{\mu} \left(\widehat{\Psi} - \Psi(\mu)\right)' V^{-1} \left(\widehat{\Psi} - \Psi(\mu)\right).$$

Here V is a diagonal matrix with the sample variances of the $\widehat{\Psi}$ along the diagonal. These variances are the basis for confidence intervals reported below for the

fixed reproducible tangible wealth in 1994 is 22.4 percent higher using the new methodology compared to previous estimates. The largest changes are in the stock of structures. In 1994 the stock of non residential structures is estimated to be 44.3 percent larger than before and the stock of residential structures 26.6 percent larger.

[8]Using the recent data, the market capital to market output ratio does not display a trend over the sample period, while the household capital to market output ratio displays a slight upward trend. In both cases the ratios are uniformly above the values reported by Greenwood, *et. al.* (1995).

dynamic correlations between household and business investment. So, with this choice of V, μ is effectively chosen so that $\Psi(\mu)$ lies as much as possible inside these confidence intervals. For the versions of the model with general home production μ does not differ very much and is roughly equal to 0.20. The share of household capital in the reduced form market production function is $(1-\alpha)\mu$ and this share is about 0.14 in the versions of the model with general home production.

4. Findings

In this section I show that the general home production formulation can reconcile RBC models with the observed lead-lag pattern between household and business investment dynamics, but time-to-build and time-to-plan in the context of pure home production cannot. Moreover, the general home production framework can account for the fact that household investment is more volatile than business investment. The pure home production models, even with realistic gestation lags in business investment, consistently predict the opposite. The discussion below is organized in terms of the different investment technologies considered.

4.1. One Quarter Time-to-Build

The pure home production model with one quarter time-to-build has the same structure as 'Model 1' in Greenwood, *et. al.* (1995) and the identically labelled model in Greenwood and Hercowitz (1991). The only difference with those models is the parameterization. The general home production model with one quarter time-to-build has not been studied before.

Table 2 shows standard business cycle statistics implied by these two models as well as the other models considered below. Tables 3 and 4 show statistics which summarize the investment dynamics which are the focus of this study. The layout of the tables is similar, with the column headings indicating the source of the reported statistics, either the U.S. data or a particular model. For the statistics in the U.S. data columns, the numbers in parenthesis are standard errors. In the column headings 'General' indicates models with general home production and 'Pure' indicates models with pure home production. Figures 2 to 4 present the information contained in Table 3 graphically. Specifically, the vertical lines with hash marks indicate plus and minus two standard deviation error bands about the point estimates for the indicated correlations. The black dots in these figures show the predictions of the various models considered for the same correlations.

The left hand columns of these figures show predictions of the pure home production models and the right hand columns show predictions of the general home production models. The rows correspond to different assumptions on the business investment technology. All statistics are based on data which has first been logged and detrended with the Hodrick-Prescott filter.

The second column of Table 2 indicates the pure home production model has implications for statistics typically studied in RBC studies that are little distinguished from the identical but differently calibrated home production models studied previously in the literature. The general home production model shares these predictions (the first column of Table 1). In fact, all the models discussed here have similar predictions for the statistics displayed in Table 2. Since these predictions have been discussed at length elsewhere, for example in Greenwood, *et. al.* (1995), I do not elaborate on them further and instead focus the rest of the discussion on the behavior of household and business investment.

Table 3 and 4 confirm that the predictions for investment dynamics in the pure model are strongly at variance with the data. Household investment co-moves strongly negatively with business investment with the contemporaneous correlation between these two variables equal to -0.60. In the data these variables co-move positively with the contemporaneous correlation statistically significant and equal to 0.39. In addition, household investment lags business investment over the business cycle, contrary to the U.S. data.[9] These dynamics are evident in the relatively large positive correlations of household investment with lags in business investment, the relatively large positive correlations of household investment with lags in output and the relative large positive correlations of business investment with future output. The final major failure of this model is respect to the relative volatility of household and business investment. The second column of Table 4 shows that the pure home production model predicts business investment is much more volatile than household investment: the ratio of the standard deviation of household investment to the standard deviation of business investment is 0.58. In the data this ratio is 1.43 and significantly greater than unity.

The pattern of co-movement and the lag-lead behavior of household and business investment in the pure home production model were first pointed out by Greenwood and Hercowitz (1991). As they emphasized, the reason is due to a basic asymmetry in pure home production models that household capital is only

[9] Formally, for variable x_t to lag (lead) variable y_t, the peak correlation of x_{t+j} with y_t would be for a positive (negative) value of j. This is the standard way of assessing lead-lag patterns between two variables. See, for example, Christiano and Vigfusson (2001).

useful for producing home consumption goods, but business capital can produce market consumption and both kinds of investment goods. This means business capital is useful for producing household capital, an input into home production, but household capital is not useful at all in market production. After a positive technology shock which raises the productivity of the market sector there is a strong incentive to move resources out of the home to build up business capital. Only later is household capital built up.

Introducing general home production, where the basic asymmetry is reversed, has a dramatic impact. Not only is there an effect encouraging positive co-movement, there is also an effect which encourages agents to build up household capital before business capital. The former arises because of the complementarity between the two kinds of capital in market production. The latter arises because household capital can not only help in the production of home goods, but in all market goods as well. Of course the magnitude of these effects depends on the share of household capital in market production, as well as other elements of the calibration. Figure 5, which displays the responses of household (dashed lines) and business investment (solid lines) to innovations in technology (the basic layout of this figure is the same as in Figures 2-4), illustrates that the effects are quite strong. With pure home production and one quarter time-to-build (first column and row) the two investments move in opposite directions in the period of a shock, with household investment dropping sharply. When general home production is added to this model (second column, first row), household investment now responds positively in the period of the shock and business investment responds with a lag.

These responses have a substantial impact on the statistics in Tables 3 and 4, moving the home production framework a long way toward the data. First, household investment co-moves positively with business investment in the general model. The contemporaneous correlation between these variables is 0.28 and within two standard deviations of the point estimate from the data. This prediction alone stands as a significant finding, given the extensive amount of research that has been conducted to overturn the pure home production model's prediction of a negative correlation.[10]

Second, the lead correlations of household investment with business investment

[10]If the share parameter μ is increased sufficiently then the two investments become negatively correlated again. This occurs since household capital eventually becomes so important in market production that after a positive technology shock agents find it optimal to substitute out of business capital and into household capital.

are larger than the contemporaneous and lag correlations. That is, household investment leads business investment over the business cycle. This is a significant finding since no previous model has been shown to be consistent with the lead-lag relationship between these variables found in the data. While qualitatively successful, this model does over predict the one period lead of household over business investment.

Third, the lead correlations of household investment with output are larger than the corresponding lag correlations and the lag correlations for business investment with output are larger than the corresponding lead correlations. These predictions also move the model closer to the data compared to the pure home production model and represent a substantial improvement compared to that model.

Finally, the first column of Table 4 indicates that in the general model household investment is more volatile than business investment and that the degree of this excess volatility is within two standard deviations of the data. This pattern of volatility has been almost as hard to achieve as the lead-lag pattern. For example, Gomme, *et. al.* (2001), while claiming success with respect to the lead-lag pattern, make no such claims with respect to the relative volatility phenomenon.

In summary, even without any differences in the investment technology across business and household investment, the general home production model represents a dramatic improvement over the pure home production model. It overcomes the latter model's three main drawbacks in terms of its predictions for household and business investment: their co-movement, lead-lag relationship and relative volatility.

4.2. Four Quarter Time-to-Build

Gomme, *et. al.* (2001) argue that adding four quarter time-to-build to a model with pure home production brings that framework into substantial conformity with the data in terms of the co-movement and lead-lag properties of household and business investment. The intuition for this potentially being the case is straightforward. With time-to-build, only a fraction of the total resources for business investment are needed in the period of a positive technology shock; the effect of a positive technology shock on business investment is spread out over the time it takes to complete a project. Compared to a model with only one quarter time-to-build, this makes it more costly to quickly install new business capital and lowers the opportunity cost of immediate investment in household capital. Since household capital is not subject to the same gestation lags, there is an increased incentive to accumulate it over business capital.

Ultimately the impact of this mechanism on the dynamics of household and business investment depends on how it matches up with competing forces, such as those induced by the fact that in pure home production models household capital is not used to produce market goods. This in turn depends on the parameterization of the model. The pure home production model with four quarter time-to-build described in this paper is the same as the model emphasized in Gomme, *et. al.* (2001). However, these authors, while using virtually the same procedure to calibrate their model, use the calibration targets in Greenwood, *et. al.* (1995), which are based on obsolete data. Using this calibration they find that the correlation of household investment at $t-1$ with output at t is slightly larger than the opposite cross-correlation, but that there is very little difference in the corresponding business investment-output correlations. In addition, they find that household and business investment are contemporaneously positively correlated. These observations form the principal basis of their conclusion that time-to-build "is an essential feature of reasonably calibrated household production models to match the cyclical properties of business and household investment (p. 3)."[11]

This conclusion may end up being correct, but the fourth column in Table 3 and the first column, second rows of Figures 2 to 4 establish that the results presented by Gomme, *et. al.* (2001) supporting it are fragile. In particular, when the new data is used to calibrate the pure home production model with four quarter time-to-build, it fails on the two dimensions emphasized as positive contributions by Gomme, *et. al.* (2001).[12] Household investment is slightly negatively corre-

[11]If one applied the criteria used by Gomme, *et. al.* (2001) to the evidence presented in the previous subsection, this evidence would refute their conclusion. That is, a model without any differences in investment technologies across household and business investment, the general home production model with one period time-to-build, would satisfy their criteria. I think their criteria fail to capture the essence of what the data say about the dynamics of business and household investment. A better criteria for confirming the lead-lag pattern is the standard one involving the dynamic correlations between two variables.

[12]There is one other difference between the two calibrations. In a departure from usual practice and the calibration procedure described by Greenwood, *et. al.* (1995), Gomme, *et. al.* (2001) do not account for growth in their model. In the notation of this paper, they assume $\gamma = 1$. I have reproduced the findings in their paper using their calibration. In this case $\rho(x_{ht-1}, y_t) - \rho(x_{ht+1}, y_t) = 0.10$ and $\rho(x_{mt-1}, y_t) - \rho(x_{mt+1}, y_t) = 0.01$, where $\rho(l_t, q_s)$ denotes the correlation between variables l_t and q_s. When their calibration is adjusted to take into account the same value for γ estimated here, $\rho(x_{ht-1}, y_t) - \rho(x_{ht+1}, y_t) = 0.05$ and $\rho(x_{mt-1}, y_t) - \rho(x_{mt+1}, y_t) = 0.04$. Even using the Gomme, *et. al.* (2001) criteria for model

lated with business investment and still lags business investment (Panel A, Table 3 and Figure 2). In addition, the correlations of household investment with future output continue to exceed the corresponding correlations with past output (Panel B, Table 3 and Figure 3) and the reverse continues to be true for the correlations of business investment with output (Panel C, Table 3 and Figure 4). The forces emphasized by these authors are certainly at work in this model. This is seen by the improvement in the investment correlations compared to the pure home production model with only one quarter time-to-build. Nevertheless, these forces are relatively weak when the model is calibrated using the new data and so the investment correlations are still far from those estimated in the data.[13]

The model with four quarter time-to-build and general home production performs much better. Consider first the correlations between household and business investment in Table 3 and in Figure 2. The incentives that come along with differences across investment in gestation lags reinforce the strong performance of the general home production model without such differences and imply a correlation pattern between household and business investment which is clearly consistent with the observed lead-lag pattern in the data. In fact the predicted correlations are remarkably close to those in the data, all falling within two standard deviations of the corresponding point estimates from the data. This strong performance is roughly matched by the investment correlations with output shown in Table 2 and in Figures 3 and 4. The correlations of household investment with output are clearly larger than the corresponding correlations with past output and the reverse is true for the correlations between business investment and output, just as in the data. Quantitatively, the model correlations are almost all within two standard deviations of the point estimates.

The impulse response functions in the second row of Figure 5 are helpful in gaining insight into the source of the substantially improved investment dynamics in this model compared to the pure home production model. In the case of pure home production, there seems to be little evidence of a consistent relationship between the two forms of investment. Sometimes they are moving together, and sometimes they move in opposite directions. To the eye, there is no apparent evidence of a lead-lag relationship. The picture for the general home production

evaluation, this does not seem to be strong evidence in favor of their model.

[13] The forces fighting against the time-to-build effects are stronger when the model is calibrated using the new data. This can be seen by comparing the impulse response function for household investment in the pure home production one quarter time-to-build model in Figure 5 with the analogous response in Figure 1 of Gomme, *et. al.* (2001). The impact response is about -6 percent with the new data compared to about -1.5 percent with the obsolete data.

model is quite different. Immediately after the innovation to technology, household investment surges. At the same time there is a slow build up of business investment. These response functions also highlight that in the pure home production case business investment seems more volatile than household investment, whereas in the general home production case the opposite seems to be true. This difference in relative volatilities is confirmed by the relevant entries in Table 4.

Overall the general home production model with four-quarter time-to-build performs much better than the corresponding pure home production model, but only moderately better than the general model with identical investment technologies for business and household investment. Accordingly it does not seem justified to conclude that time-to-build is "essential" to account for the observed heterogeneous investment dynamics.

4.3. Four Quarter Time-to-Build with a Planning Phase

Is the poor performance of the pure home production model with differences in investment gestation lags due to an improper specification of time-to-build? One way to assess this is to consider the addition of a planning phase to the four quarter time-to-build formulation. On the one hand this is well motivated on empirical grounds and seems like a reasonable alternative to the conventional time-to-build specification. On the other hand, it seems possible that adding another reason why business investment may lag household investment should improve the performance of this model.

To some extent this latter possibility turns out to be true. Table 3 and the last row of Figure 2 show that the maximal lead correlation exceeds the maximal lag correlation of household versus business investment. Unfortunately the contemporaneous correlation is now much more negative than in the conventional time-to-build case. The reason for this can be seen by studying the impulse response functions in the last row, left-hand column of Figure 5. Time-to-plan certainly encourages a surge in household investment in advance of a build-up of business investment. However, as soon as the resource flow into the newly initiated business investment projects rises, there is a swift cut-back in household investment. Lowering the initial resource flow into business investment projects exacerbates this problem and contributes to a much larger negative contemporaneous correlation between the two kinds of investment.

If one ignores the household-business investment correlations and focuses only on the investment-output correlations, the pure home production model does look better. However, it does not look as good when it is compared to the model with the same market investment technology, but with general home production. The empirically desirable lead-lag and co-movement properties of household and business investment present in the general home production model considered in the previous subsection continue to be present when a planning phase is added to that model. Finally, Table 4 indicates the greater volatility of household investment compared to business investment continues to be the case with this version of the general home production model, in stark contrast to the comparable pure home production model.

5. Conclusion

This paper has demonstrated that RBC models can be reconciled with the comovement, lead-lag pattern and relative volatility of household and business investment. The feature of the models considered here which contributes most to this finding is the fact that household capital is useful in market production, what I have termed general home production. Differences in the time-to-build and plan characteristics of household and business investment add somewhat to the success of the general home production framework, but do not seem to be crucial to its success. When these model characteristics are incorporated into a standard home production framework they do not account for the observed heterogeneous investment dynamics. The results support the conclusion that future models of home production which seek to address aggregate data should adopt the general formulation developed in this paper.

The main drawback of the current research is that the use of household capital in market production was not calibrated with independent evidence. It was estimated using some of the correlations of interest. This is not as much a drawback as might at first seem, since only one new parameter has been added to previously studied models, yet the model does substantially better than these models on multiple dimensions. Still, it would be very interesting to identify the magnitude of the complementarity of household capital with other inputs into market production using micro data. This task is left to future research.

Data Appendix

The flow data sources are from the Haver Analytics database while the capital stock series were downloaded directly from the web site `www.stat-usa.gov`. All real series are in chained 1996 dollars. Except where noted, the original source for the series is the Bureau of Economic Analysis. To form data counterparts of model variables some series were added together or a series was subtracted from another. In these cases, the appropriate chain-weighting procedure was used. This requires price deflators and so for the series requiring price deflators I list both real and nominal series. Otherwise I just list the real series.

The mnemonics for the series taken from the Haver Analytics database are in parenthesis after a description of the series as follows: gross domestic product (GDPH), nonresidential fixed investment (FNH), residential fixed investment (nominal – FR, real – FRH), consumption of non-durables (nominal – CN, real – CNH), consumption of services (nominal CS, real CSH), consumer durable expenditures (nominal – CD, real – CDH), consumption of housing services (nominal – CSR, real – CSRH), hours of private wage and salary workers on nonfarm payrolls (LHTPRIVA, original source is Bureau of Labor Statistics). The downloaded BEA capital stock series are taken from data files 1KCU.TXT (nominal series) and 15KRE.TXT (real series).

The data counterparts for the model variables are as follows: output is GDP less consumption of housing services, consumption is the sum of nondurables and services consumption less housing services, business investment is nonresidential fixed investment, household investment is the sum of residential fixed investment and durables consumption expenditures, total investment is the sum of household and business investment, hours is private hours on nonfarm payrolls. The capital stock series are derived analogously to the investment series.

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Table 1: Parameter Values

Parameter	One Quarter Time-to-Build General	One Quarter Time-to-Build Pure	Four Quarter Time-to-Build General	Four Quarter Time-to-Build Pure	Four Quarter Time-to-Build with Planning Phase General	Four Quarter Time-to-Build with Planning Phase Pure
			Preferences			
β	0.991	0.991	0.991	0.991	0.991	0.991
ψ	0.479	0.713	0.476	0.706	0.470	0.707
η	0.661	0.828	0.652	0.817	0.650	0.819
			Home Production			
μ	0.201	0	0.201	0	0.207	0
ϕ	0.172	0.303	0.178	0.306	0.171	0.305
δ_h	0.015	0.015	0.015	0.015	0.015	0.015
			Market Production			
α	0.302	0.302	0.312	0.312	0.310	0.310
δ_k	0.014	0.014	0.014	0.014	0.014	0.014
J	1	1	4	4	4	4
ω_1	1	1	0.25	0.25	0.30	0.30
ω_2	0	0	0.25	0.25	0.30	0.30
ω_3	0	0	0.25	0.25	0.30	0.30
ω_4	0	0	0.25	0.25	0.10	0.10
			Government			
τ_n	0.25	0.25	0.25	0.25	0.25	0.25
τ_k	0.70	0.70	0.70	0.70	0.70	0.70
			Labor-augmenting Technology			
γ	1.00528	1.00528	1.00528	1.00528	1.00528	1.00528
ρ	0.95	0.95	0.95	0.95	0.95	0.95
σ	0.014	0.011	0.014	0.011	0.014	0.011

Note: See the text for the meaning of the column headings.

Table 2: Standard Business Cycle Statistics in Various Models

Statistic[a]	U.S Data[b]	One Quarter Time-to-Build[c]		Four Quarter Time-to-Build		Four Quarter Time-to-Build with Planning Phase	
		General	Pure	General	Pure	General	Pure
σ_y	1.91 (0.17)	1.34	1.52	1.31	1.37	1.31	1.37
σ_{n_m}/σ_y	1.04 (0.04)	0.42	0.43	0.43	0.42	0.42	0.42
σ_c/σ_y	0.46 (0.03)	0.38	0.37	0.39	0.39	0.39	0.39
σ_x/σ_y	2.59 (0.15)	3.39	3.44	3.39	3.38	3.39	3.38
$\rho(n_{mt}, y_t)$	0.89 (0.02)	0.99	0.99	0.99	0.99	0.99	0.99
$\rho(c_t, y_t)$	0.79 (0.04)	0.97	0.97	0.96	0.97	0.96	0.97
$\rho(x_t, y_t)$	0.76 (0.08)	0.99	0.99	0.99	0.98	0.99	0.99

Notes: a – σ_l denotes the standard deviation of variable l, $\rho(l_t, q_s)$ denotes the cross-correlation between variable l_t and variable q_s, and $x = x_m + x_h$; b – Point estimate with standard error in parenthesis based on U.S. data over the sample period 1948:I-1999:IV. Standard errors computed using a GMM procedure. For estimation of the relevant zero-frequency spectral density, a Bartlett window truncated at lag five was used. For data sources, see the appendix; c – For parameter values corresponding to the different models indicated in the column headings, see Table 1.

Table 3: Dynamics of Household and Business Investment in Various Models

Statistic	U.S Data	One Quarter Time-to-Build General	One Quarter Time-to-Build Pure	Four Quarter Time-to-Build General	Four Quarter Time-to-Build Pure	Four Quarter Time-to-Build with Planning Phase General	Four Quarter Time-to-Build with Planning Phase Pure
Panel A – Household Investment Correlations with Business Investment							
$\rho(x_{ht-2}, x_{mt})$	0.69	0.65	-0.08	0.78	0.10	0.81	0.20
	(0.08)						
$\rho(x_{ht-1}, x_{mt})$	0.59	0.87	-0.07	0.68	0.15	0.66	0.26
	(0.07)						
$\rho(x_{ht}, x_{mt})$	0.39	0.28	-0.60	0.33	-0.02	0.30	-0.35
	(0.07)						
$\rho(x_{ht+1}, x_{mt})$	0.07	0.15	0.53	0.04	0.27	0.03	-0.01
	(0.08)						
$\rho(x_{ht+2}, x_{mt})$	-0.20	0.04	0.42	-0.09	0.35	-0.08	0.22
	(0.10)						
Panel B – Household Investment Correlations With Output							
$\rho(x_{ht-2}, y_t)$	0.63	0.47	0.01	0.45	0.15	0.45	0.12
	(0.09)						
$\rho(x_{ht-1}, y_t)$	0.67	0.64	0.08	0.65	0.31	0.65	0.25
	(0.09)						
$\rho(x_{ht}, y_t)$	0.60	0.86	0.23	0.89	0.57	0.88	0.48
	(0.10)						
$\rho(x_{ht+1}, y_t)$	0.36	0.25	0.80	0.34	0.38	0.33	-0.01
	(0.12)						
$\rho(x_{ht+2}, y_t)$	0.08	0.11	0.59	0.01	0.32	0.00	0.12
	(0.13)						
Panel C – Business Investment Correlations With Output							
$\rho(x_{mt-2}, y_t)$	0.24	0.32	0.43	0.28	0.48	0.28	0.41
	(0.09)						
$\rho(x_{mt-1}, y_t)$	0.51	0.51	0.57	0.47	0.63	0.47	0.53
	(0.07)						
$\rho(x_{mt}, y_t)$	0.75	0.72	0.63	0.73	0.80	0.71	0.64
	(0.04)						
$\rho(x_{mt+1}, y_t)$	0.81	0.99	-0.02	0.91	0.51	0.91	0.71
	(0.05)						
$\rho(x_{mt+2}, y_t)$	0.71	0.69	-0.08	0.86	0.25	0.88	0.33
	(0.08)						

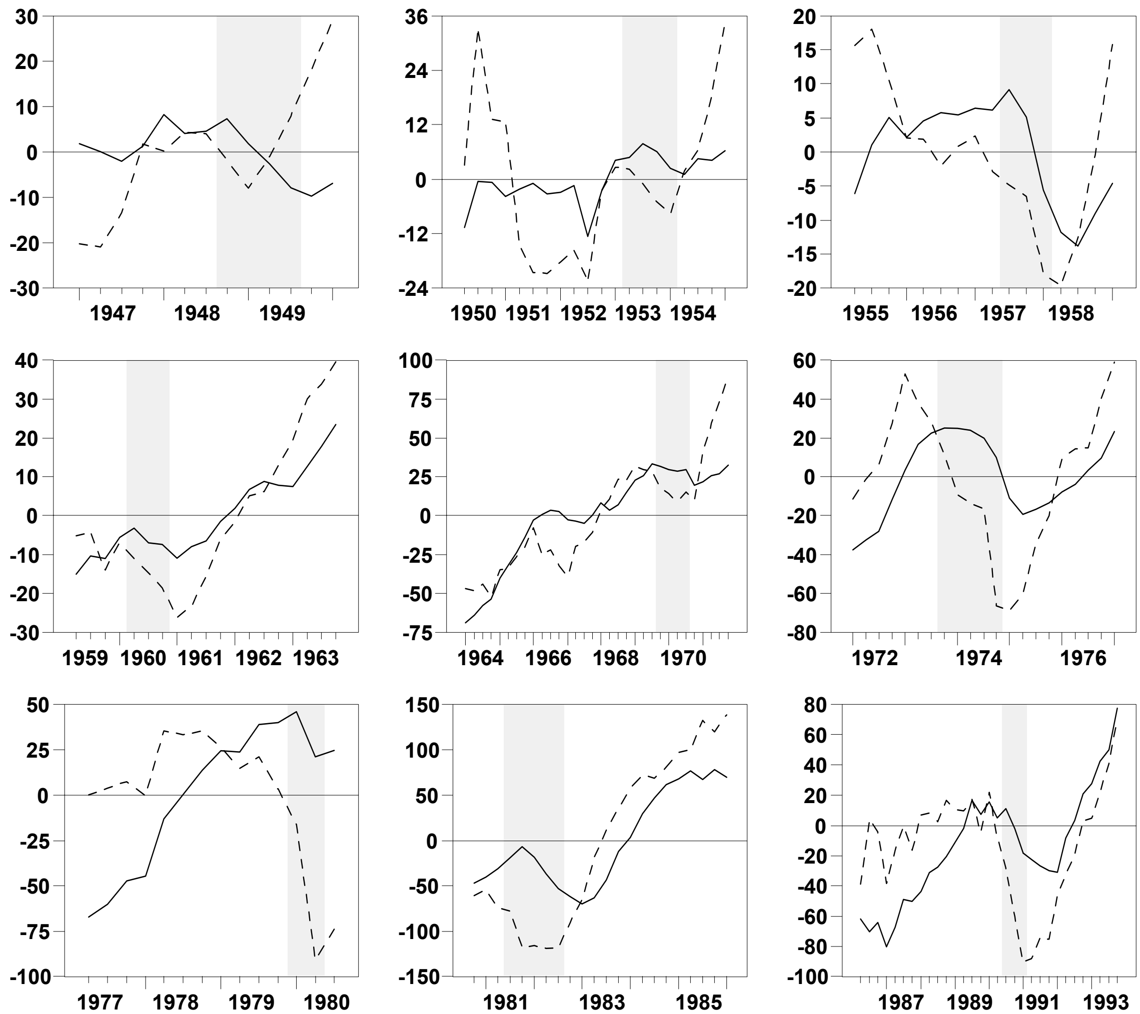
Note: See the notes to Table 2.

Table 4: Relative Volatility of Household and Business Investment in Various Models

Statistic	U.S Data	One Quarter Time-to-Build		Four Quarter Time-to-Build		Four Quarter Time-to-Build with Planning Phase	
		General	Pure	General	Pure	General	Pure
$\sigma_{x_h}/\sigma_{x_m}$	1.43	1.24	0.58	1.53	0.60	1.50	0.74
	(0.12)						

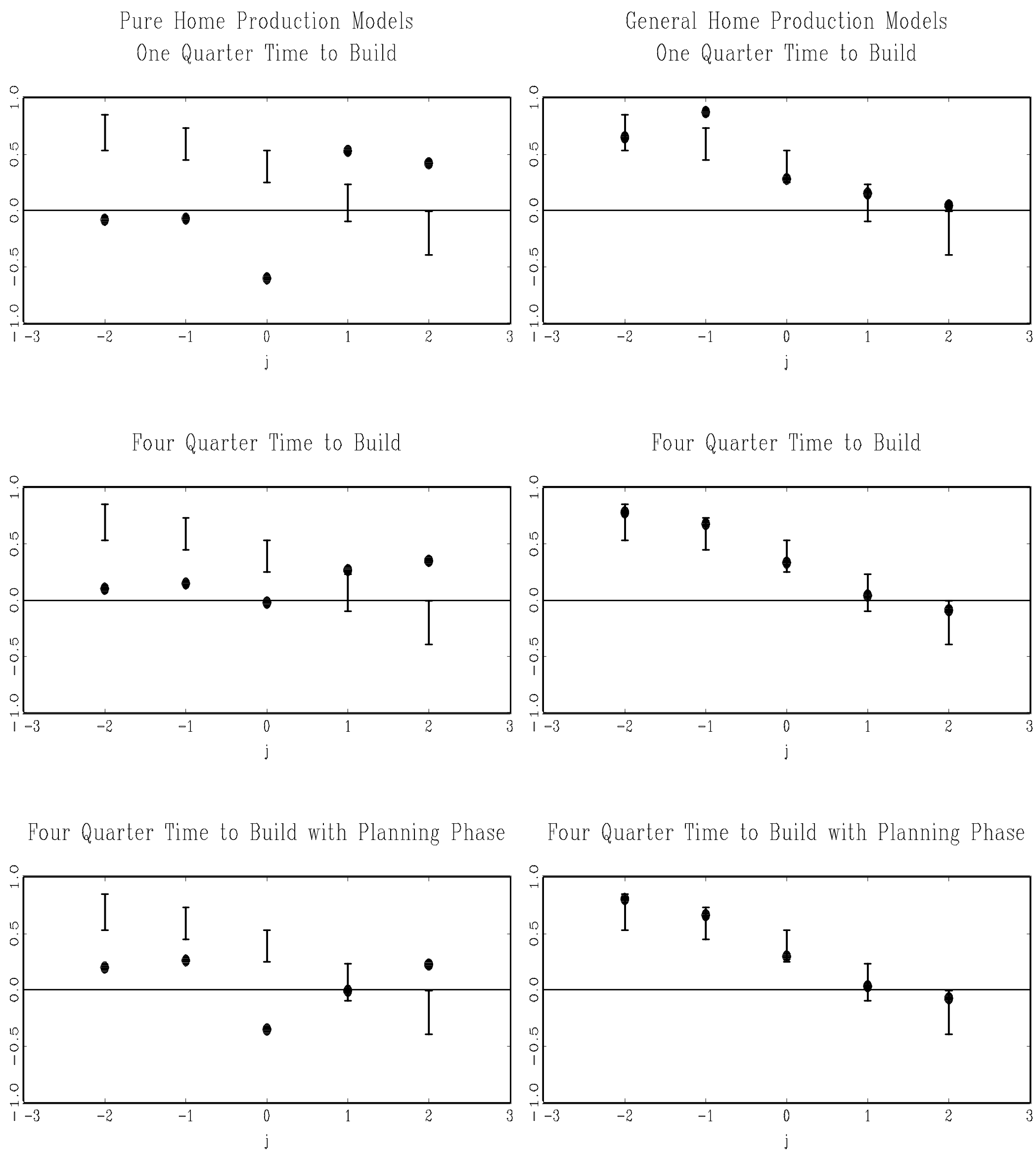
Note: See the notes to Table 2.

Figure 1: Household Investment Leads Business Investment Over the Business Cycle



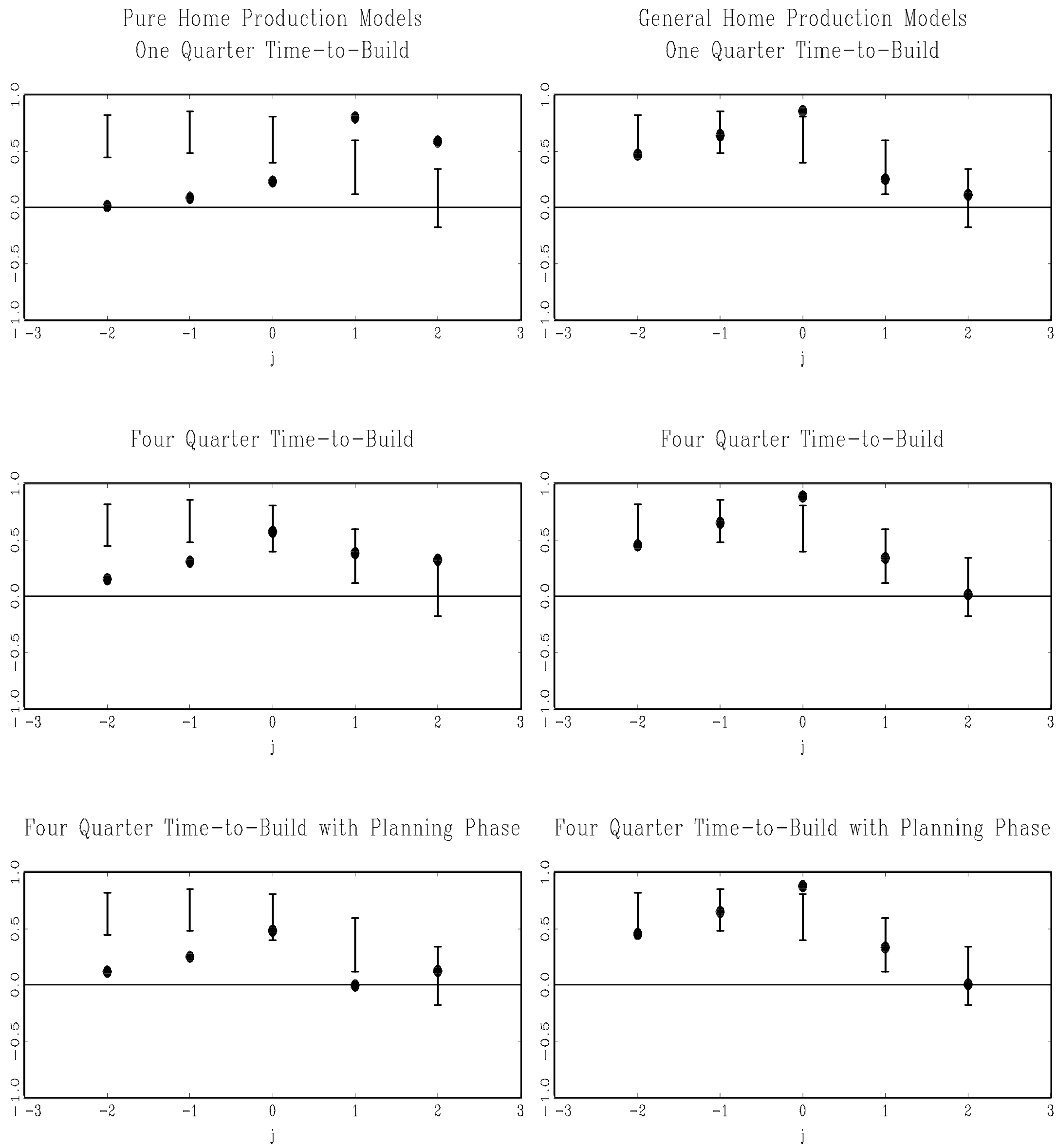
Note: The plots cover consecutive sample periods from 1947:I to 1994:IV. The solid line is the level of business investment and the dashed line is the level of household investment, both in billions of chained 1996 dollars. In each plot the series have been de-meaned using the mean of the series over the sample period corresponding to the plot. The shaded regions correspond to business cycle recessions as dated by the NBER.

Figure 2: Model and Estimated Correlations Between Household Investment at $t+j$ and Business Investment at t



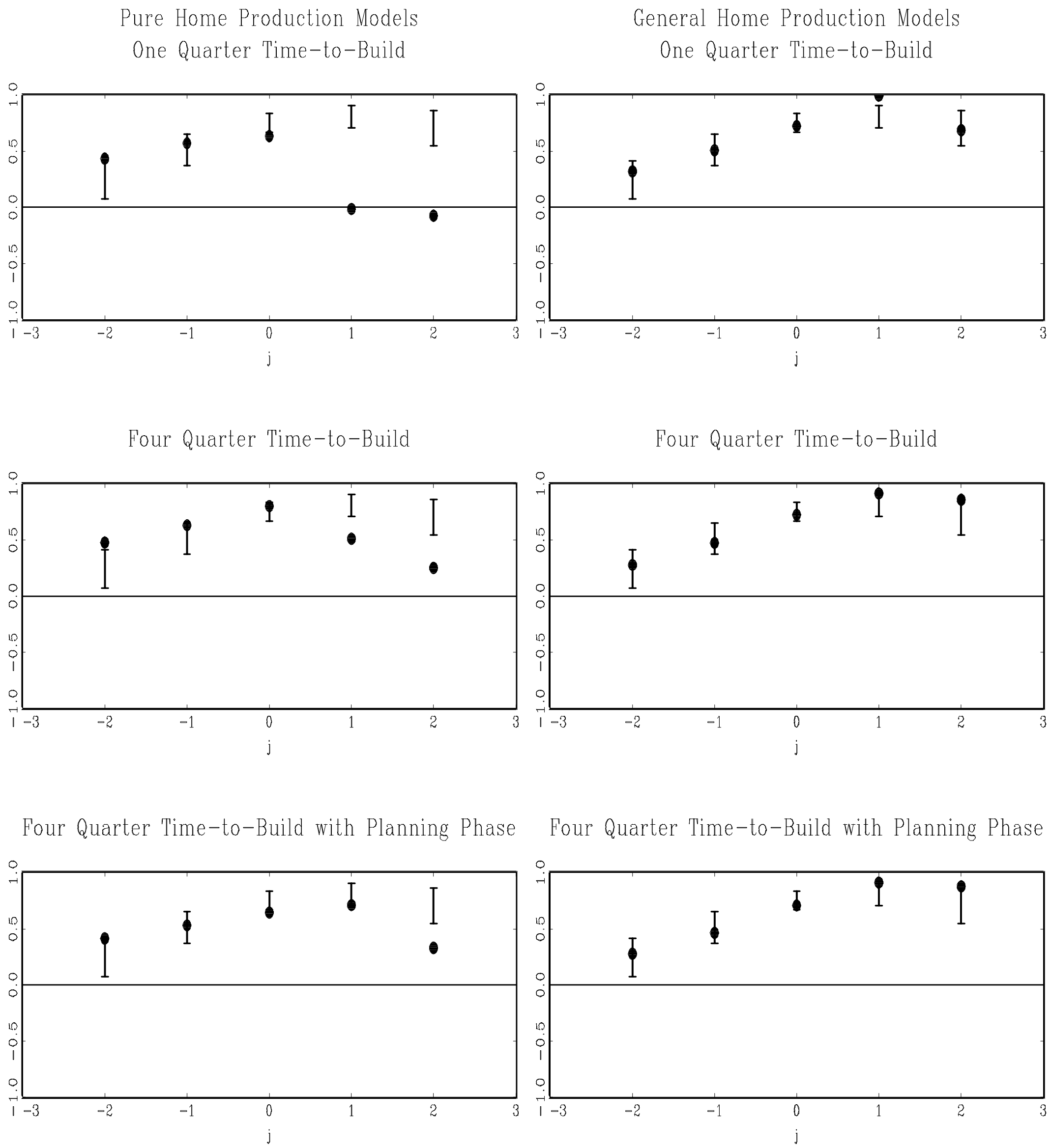
Note: The vertical lines with hash marks indicate plus and minus two standard deviation error bounds around the point estimates of the dynamic correlations between household investment at time $t+j$ and market investment at time t, $j=-2,-1,...,2$. The black dots show the corresponding correlation implied by the indicated model.

Figure 3: Model and Estimated Correlations Between Household Investment at $t+j$ and Output at t



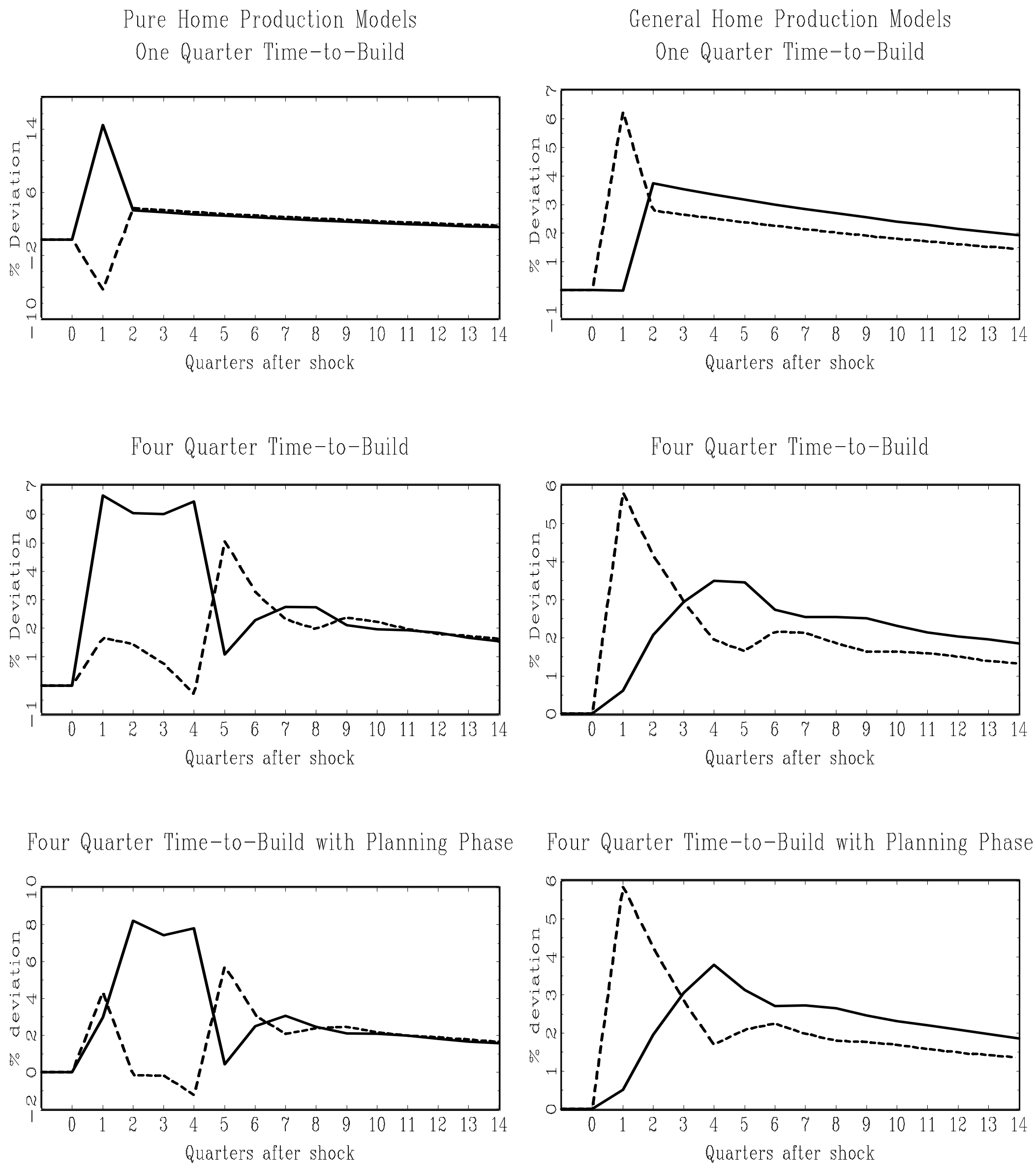
Note: The vertical lines with hash marks indicate plus and minus two standard deviation error bounds around the point estimates of the dynamic correlations between household investment at time $t+j$ and market output at time t, $j = -2, -1, ..., 2$. The black dots show the corresponding correlation implied by the indicated model.

Figure 4: Model and Estimated Correlations Between Business Investment at $t+j$ and Output at t



Note: The vertical lines with hash marks indicate plus and minus two standard deviation error bounds around the point estimates of the dynamic correlations between market investment at time $t+j$ and market output at time t, $j = -2, -1, ..., 2$. The black dots show the corresponding correlation implied by the indicated model.

Figure 5: Model Responses of Investment to Innovations in Technology



Note: The solid lines correspond to responses of business investment and the dashed lines to responses of household investment.