Home Production Meets Time to Build

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An innovation in this paper is to introduce a time-to-build technology for the production of market capital into a model with home production. Our main finding is that the two anomalies that have plagued all household production models—the positive correlation between business and household investment, and household investment's leading business investment over the business cycle—are resolved when time to build is added.

I. Introduction

The household sector is large. For example, Greenwood and Hercowitz (1991) report that the stock of household capital actually exceeds market capital. Further, Benhabib, Rogerson, and Wright (1991) estimate that the output of the household sector may be as much as half that of the market sector and that labor hours in the home sector are almost as great as in the market sector. Additionally, home investment (pur-

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chases of consumer durables and residential housing) exceeds market investment (purchases of nonresidential structures and equipment). Consequently, as suggested by Benhabib et al. and Greenwood and Hercowitz, it seems plausible that accounting for home production and its interaction with market production may be important for understanding many macroeconomic phenomena. Yet, it seems fair to say that household production has not really taken hold in the profession despite the many papers that have pursued that idea and refined the necessary measurements. A reason may be that, in light of household production theory, there are too many anomalies in the data. This paper attempts to settle the issue of the importance of household production for understanding the business cycle.

One key anomaly is that there is a *positive* correlation between market and home investment in the U.S. data, whereas the basic home production models of Benhabib et al. (1991) and Greenwood and Hercowitz (1991) predict a *negative* comovement.[1] Greenwood and Hercowitz obtain a positive correlation by assuming that (*a*) the household production function exhibits strong complementarity between home capital and home labor, (*b*) preferences allow a high degree of substitutability between market and home consumption goods, and (*c*) the shocks to market and home productivity are perfectly correlated.[2]

More important, the U.S. data reveal that household investment *leads* the cycle by about one quarter whereas market investment *lags* by about a quarter. As shown below, both the Benhabib et al. and Greenwood and Hercowitz models predict exactly the opposite pattern: that home investment *lags* the cycle and market investment *leads*. This phase shift pattern is such an interesting and striking feature of the data that home production models that cannot replicate this phase shift must be considered a failure.

Specifications of preferences and technologies do exist such that home production models *are* consistent with the business cycle facts we emphasize. Greenwood and Hercowitz show that greater complementarity between capital and hours in the home production function improves on their basic home production model. As discussed below, however, such preferences and technologies appear to be inconsistent with key balanced growth facts.

The principal innovation of this paper is to introduce a time-to-build technology for the production of market capital into an otherwise stan-

[1] The correlation between the two investment series has received considerable attention in the literature. A short, and no doubt incomplete, list of such papers includes Baxter (1996), Fisher (1997), and Hornstein and Praschnik (1997).

[2] As shown in Greenwood, Rogerson, and Wright (1995), perfect correlation in the shocks is not necessary to generate the positive correlation in market and home investment, although the shocks must be *very highly* correlated.

dard household production model. With time to build, initiating a market investment project in the current period yields useful capital several periods hence. Furthermore, starting a project today implies a commitment of resources to this project not only in the current period but in all periods leading to completion of the project. By way of contrast, home production is subject to a standard one-period time to build; that is, investment today yields home capital in the next period.

In the basic home production model, an improvement in market productivity leads, on impact, to a sharp rise in market investment and a fall in home investment. This pattern arises because market investment allows greater future market output. As a result, it is only in subsequent periods that home investment rises. With time to build, only a fraction of the total resources for market investment are needed in the impact period. That is, the impact response on market investment is spread out over the length of time it takes to complete a project. In essence, time to build makes it infeasible to quickly bring on line new units of market capital. At the same time, time to build reduces the cost (in terms of current consumption and leisure) of increasing the market capital stock at longer horizons. These two effects induce a positive comovement between market and home investment. The same mechanisms also operate in regard to the lead-lag patterns of the two investment series. So, it appears that time to build is an essential feature for calibrated household production models to match the cyclical properties of market and home investment.

II. The Economic Environment

A. *Households*

The representative household has preferences over market consumption, c_{Mt}, home consumption, c_{Ht}, market hours, h_{Mt}, and home hours, h_{Ht}, summarized by

$$E_0 \sum_{t=0}^{\infty} \beta^t U(c_{Mt}, c_{Ht}, h_{Mt}, h_{Ht}), \quad 0 < \beta < 1.$$

The momentary utility function has the following form:

$$U(c_M, c_H, h_M, h_H) = \begin{cases} \omega \ln C(c_M, c_H) + (1-\omega)\ln(1 - h_M - h_H) & \text{if } \gamma = 1 \\ \dfrac{[C(c_M, c_H)^{\omega}(1 - h_M - h_H)^{1-\omega}]^{1-\gamma} - 1}{1-\gamma} & \text{if } 0 < \gamma < 1 \text{ or } \gamma > 1, \end{cases}$$

where the consumption aggregator is

$$C(c_M, c_H) = \begin{cases} c_M^{\psi} c_H^{1-\psi} & \text{if } \xi = 0, \\ [\psi c_M^{\xi} + (1-\psi) c_H^{\xi}]^{1/\xi} & \text{if } \xi < 0 \text{ or } 0 < \xi < 1. \end{cases}$$

A household faces a number of constraints. First, its budget constraint is

$$c_{Mt} + x_{Mt} + x_{Ht} = (1 - \tau_K) r_t k_{Mt} + (1 - \tau_H) w_t h_{Mt} + \delta_M \tau_K k_{Mt} + \tau_t.$$

Here, k_{Mt} is the household's stock of market capital, r_t is the rental price of capital, w_t is the real wage rate, and x_{Mt} and x_{Ht} are investment in market and home capital, respectively. Capital income is taxed at the rate τ_K, and labor income is taxed at the rate τ_H. Note that the tax rate τ_K in the household's budget constraint applies to gross capital income. The term $\delta_M \tau_K k_{Mt}$ captures the depreciation allowance built into the U.S. tax code. Finally, τ_t is a lump-sum transfer from the government.

Second, as in Kydland and Prescott (1982), capital projects are subject to a J-period time-to-build technology constraint. Specifically, starting a project at date t requires investment of resources at dates t, $t+1, \ldots, t+J-1$, with the capital finally being ready for use at date $t+J$. A project j periods from completion requires a fraction ϕ_j of the total resources required for that project. Let s_{jt} be the number of projects that are j periods from completion at date t. Then total market investment is

$$x_{Mt} = \sum_{j=1}^{J} \phi_j s_{jt}.$$

Further, the project commitments evolve according to

$$s_{j-1,t+1} = s_{jt}, \quad j = 2, \ldots, J.$$

That is, a project that is j periods from completion at date t will be $j-1$ periods from completion in the next period.

Third, the household's capital stocks evolve according to

$$k_{Mt+1} = (1 - \delta_M) k_{Mt} + s_{1t},$$

$$k_{Ht+1} = (1 - \delta_H) k_{Ht} + x_{Ht},$$

where δ_M and δ_H are the depreciation rates of market and home capital, respectively. Recall that s_{1t} represents the number of projects that are one period from completion as of the beginning of period t.

Finally, home production is described by

$$c_{Ht} = H(k_{Ht}, h_{Ht}; z_{Ht}).$$

The home production function has the form

$$H(k_{Ht}, h_{Ht}; z_{Ht}) = \begin{cases} e^{z_{Ht}} k_{Ht}^{\eta} h_{H}^{1-\eta} & \text{if } \zeta = 0 \\ e^{z_{Ht}} [\eta k_{Ht}^{\zeta} + (1-\eta) h_{Ht}^{\zeta}]^{1/\zeta} & \text{if } \zeta < 0 \text{ or } 0 < \zeta < 1. \end{cases}$$

The home productivity shock evolves as

$$z_{H,t+1} = \rho_H z_{Ht} + \epsilon_{Ht}, \quad \epsilon_{Ht} \sim N(0, \sigma_H^2).$$

B. *Firms*

Goods-producing firms act competitively and seek to maximize profits,

$$F(k_{Mt}, h_{Mt}; z_{Mt}) - r_t k_{Mt} - w_t h_{Mt}.$$

The production function is Cobb-Douglas,

$$F(k_{Mt}, h_{Mt}; z_{Mt}) = e^{z_{Mt}} k_{Mt}^{\alpha} h_{Mt}^{1-\alpha},$$

and the market productivity shock evolves according to

$$z_{Mt+1} = \rho_M z_{Mt} + \epsilon_{Mt}, \quad \epsilon_{Mt} \sim N(0, \sigma_M^2).$$

C. *Government*

In this economy, the government raises revenue via labor and capital taxes, rebating the proceeds to households in a lump sum:

$$T_t = \tau_K r_t k_{Mt} + \tau_H w_t h_{Mt} - \delta_M \tau_K k_{Mt}.$$

As discussed in Greenwood et al. (1995), the reason for including taxes is that they have important implications for the calibration; this issue is discussed in more detail in Section III.

III. Calibration

The model is calibrated using the procedure set out by Kydland and Prescott (1982). In particular, as many parameters as possible are set in advance on the basis of a priori information concerning their magnitude or so as to match certain long-run averages observed in the postwar U.S. economy.

The parameters that need to be assigned values are summarized in table 1.[3] Except for the parameters governing time to build, the values either are the same as in model 1 of Greenwood et al. (1995) or are calibrated to match the same long-run averages. To start, a model period corresponds to one quarter. Setting the discount factor, β, to $1.06^{-1/4}$

[3] Table 1 summarizes parameter values for the four-period time-to-build model. For the benchmark home production model, the calibration procedure implies slightly different values for the parameters ω, ψ, η, and α.

TABLE 1
BASELINE PARAMETERS

	Value	Definition
Preferences:		
β	.9855	Discount factor
ω	.6755	Consumption-leisure weight
γ	1.0	Coefficient of relative risk aversion
ψ	.5583	Market-home consumption weight
ξ	.0	Constant elasticity of substitution parameter in consumption aggregator
Home production:		
η	.3526	Capital-labor weight
ζ	.0	Constant elasticity of substitution parameter
δ_H	.027	Depreciation rate
Time to build:		
J	4	Number of project periods
ϕ_j	.25	Fraction of resources used at stage j
Market production:		
α	.3267	Capital share
δ_M	.0295	Depreciation rate
Government:		
τ_H	.25	Tax rate on labor income
τ_K	.70	Tax rate on capital income
Shocks:		
ρ_M	.95	Market shock autocorrelation
ρ_H	.95	Home shock autocorrelation
σ_M	.00763	Standard deviation of market shock innovation
σ_H	.00763	Standard deviation of home shock innovation
corr$(\epsilon_{Mt}, \epsilon_{Ht})$	.6667	Correlation of the innovations

thus generates an annual real interest rate of 6 percent in the steady state. The coefficient of relative risk aversion, γ, is set to one, which implies logarithmic preferences. The home production function and consumption aggregator are assumed to be Cobb-Douglas; thus $\xi = \zeta = 0$. Evidence on U.S. Solow residuals motivates setting $\rho_M = 0.95$ and $\sigma_M = 0.00763$ (see Prescott 1986).

In the absence of hard evidence to guide the choice of the stochastic process describing the home technology shock, it is assumed that the home shock process is the same as that of the market shock, that is, $\rho_H = 0.95$ and $\sigma_H = 0.00763$. The correlation between the innovations to the market and home shocks (i.e., between ϵ_{Mt} and ϵ_{Ht}) is set to $\frac{2}{3}$. In the home production literature to date, the value of this correlation has important implications for the cyclical behavior of home and market investment. In particular, Greenwood and Hercowitz (1991) require virtually a perfect correlation for their household production model to predict a positive correlation between the two investment series. The parameterization of our baseline model—in particular, the logarithmic preferences and Cobb-Douglas home production function and consumption aggregator—implies enough separability that the home production shock affects only home consumption and aggregated consumption. That is, none of the market variables respond to a home productivity shock. Consequently, apart from home and aggregated consumption, none of the baseline model results would change if the home productivity shock were simply dropped from the model.

As in Kydland and Prescott (1982), when time to build is in play, it takes four quarters to complete a market investment project, and each period one-fourth of the total resources are used. Thus $J = 4$ and $\phi_j = \frac{1}{4}$ for $j = 1, 2, 3, 4$. Models without time to build correspond to a one-period time to build. That is, $J = 1$ and $\phi_1 = 1$. The longer gestation time for market investment projects vis-à-vis home investment projects is motivated by empirical plausibility. It is possible to compare time to build for structures in the home and market sectors. On average, single family structures take three to six months to complete, two- to four-unit buildings about eight months, and buildings with five units or more about nine to 10 months. Nonresidential structures average between 22 and 24 months. Once we add in other durables to the residential sector or equipment to the nonresidential sector, our estimates of one quarter for home capital and four quarters for market capital are not unreasonable and are probably conservative with respect to the difference between the two.[4]

The parameters ω, ψ, α, η, δ_H, and δ_M are chosen such that in steady state, (1) market hours, h_M, equal to $\frac{1}{3}$ and home hours, h_H, equal to $\frac{1}{4}$ (these values are consistent with evidence from time use surveys); (2) market capital, k_M, is four times market output, and home capital, k_H, is five times market output; and (3) market investment, x_M, is 11.8 percent of market output, and home investment, x_H, is 13.5 percent of market output.

The tax rates are set to $\tau_K = 0.70$ and $\tau_H = 0.25$. Along with the restrictions above, these tax rates imply the values for ω, ψ, α, η, δ_H, and δ_M given in table 1. At first blush, the tax rate on capital may seem quite high. It is, however, well within the range of *effective* capital income tax rates reported by Feldstein, Dicks-Mireaux, and Poterba (1983). Further, Greenwood et al. (1995) argue that τ_K should also incorporate the effects of the cornucopia of regulations faced by business. They also point out that τ_K is an important parameter for generating a reasonable capital share parameter in the market sector (given the restrictions above, in particular the market capital to market output ratio). Models without

[4] Data for residential structures are taken from the National Association of Home Builders and the U.S. Bureau of the Census's Survey of Construction. Data for nonresidential structures are taken from Mayer (1960) and Koeva (1999).

TABLE 2
U.S. ECONOMY: SELECTED MOMENTS

	Standard Deviation	Cross Correlation of Real Output with:								
		x_{t-4}	x_{t-3}	x_{t-2}	x_{t-1}	x_t	x_{t+1}	x_{t+2}	x_{t+3}	x_{t+4}
Gross domestic product	1.66	.13	.37	.62	.85	1.00	.85	.62	.37	.13
Market consumption	.95	.34	.53	.68	.79	.80	.67	.48	.28	.07
Market investment	4.73	−.14	.04	.29	.56	.80	.87	.82	.68	.46
Household investment	6.74	.47	.61	.74	.80	.76	.52	.24	−.03	−.25
Total investment	4.95	.29	.47	.68	.84	.90	.76	.53	.26	−.00
Aggregate hours	1.79	−.11	.11	.38	.66	.88	.91	.80	.63	.41
Productivity	.86	.49	.48	.41	.26	.10	−.26	−.48	−.59	−.59

home production do not seem to have such a problem (related to income taxation), for they calibrate to a much higher capital/output ratio since market and home capital are lumped together.

IV. Findings

Since the parameterization of the baseline model is chosen to be consistent with several other papers incorporating home production, it also shares their successes and failures. Although attention will be focused on the cyclical pattern of market and home investment, a fairly comprehensive set of business cycle moments can be found in tables 2 (for the U.S. economy) and 3 (for the household production only baseline model). For all tables of business cycle moments, the data have been detrended by taking logarithms and Hodrick-Prescott filtering. For a more complete assessment of the baseline model's strengths and weaknesses, see model 1 of Greenwood et al. (1995).

One feature, emphasized by Greenwood and Hercowitz (1991) and Greenwood et al. (1995), is the contemporaneous correlation between market and home investment. Table 5 below reports that for the U.S. economy this correlation is .41, whereas the "standard" household production model predicts a value of −.10. It was this failure of the standard model that led Greenwood and Hercowitz to make the following assumptions: (1) the market and home shocks are perfectly correlated, and (2) there is a high degree of substitutability in the consumption aggregator ($\xi = \frac{2}{3}$) and a high degree of complementarity in the home production function ($\zeta = -\frac{1}{2}$).[5] These assumptions are problematic.

[5] A referee has suggested that in a vintage capital model, there may be differences in the long- and short-run complementarity between capital and labor. In this light, perhaps one can view these alternative specifications in the home production literature as stand-ins for a vintage capital model.

TABLE 3
HOME PRODUCTION ONLY: SELECTED MOMENTS

	Standard Deviation	Cross Correlation of Real Output with:								
		x_{t-4}	x_{t-3}	x_{t-2}	x_{t-1}	x_t	x_{t+1}	x_{t+2}	x_{t+3}	x_{t+4}
Output	1.43	.10	.27	.47	.73	**1.00**	.73	.47	.27	.10
Consumption:										
Market	.58	−.02	.15	.38	.67	**.97**	.76	.57	.40	.26
Home	.88	.02	.12	.24	.38	**.52**	.37	.27	.19	.11
Aggregated	.63	.00	.15	.34	.58	**.83**	.62	.46	.32	.20
Investment:										
Market	7.45	.19	.32	.46	.64	**.78**	.16	.03	−.05	−.11
Home	4.58	−.02	.07	.19	.33	**.53**	.96	.66	.40	.21
Total	4.03	.15	.31	.51	.75	**.99**	.71	.43	.20	.03
Hours:										
Market	.58	.18	.33	.52	.76	**.99**	.69	.40	.17	−.01
Home	.29	−.18	−.33	−.52	−.76	**−.99**	−.69	−.40	−.17	.01
Total	.21	.18	.33	.52	.76	**.99**	.69	.40	.17	−.01
Capital:										
Market	.51	−.31	−.16	.04	.32	**.65**	.70	.69	.64	.57
Home	.37	−.49	−.45	−.37	−.25	**−.06**	.27	.49	.61	.67
Total	.40	−.48	−.42	−.32	−.16	**.06**	.35	.54	.64	.68
Productivity	.85	.05	.22	.43	.71	**.99**	.75	.52	.33	.17

For instance, while there is little direct evidence on the size of the correlation between the market and home shocks, indirect evidence suggests that it is less than perfect. Regulatory changes, by way of example, are unlikely to have the same effect on market and home production. Furthermore, as pointed out by Kydland (1995), it is hard to reconcile any deviation from Cobb-Douglas (for either the home production function or consumption aggregator) with the fact that the price of durable goods relative to nondurables has exhibited a secular decline whereas the expenditure share of durables has remained fairly constant.[6] Benhabib et al. (1991) face similar challenges in regard to their parameter choices.[7]

Less attention has been placed on the lead-lag patterns of the investment series. In the U.S. data, home investment *leads* the cycle by one quarter and market investment *lags* by one quarter. By way of contrast, the baseline model predicts that home investment *lags* output by a quarter and that market investment is coincident to leading. That is,

[6] It would be fairly straightforward to add to our model a relative price of durables, $q_t = q_0 \exp(q_1 t)$. For $q_1 < 0$, the relative price of durables falls over time. It is well known that Cobb-Douglas preferences imply constant expenditure shares. Consequently, given the functional form for the utility function, we require that both the consumption aggregator and home production function be of the Cobb-Douglas variety.

[7] McGrattan, Rogerson, and Wright (1997) cannot address this issue since they ignore the price data.

TABLE 4
HOME PRODUCTION WITH TIME TO BUILD: SELECTED MOMENTS

	Standard Deviation	Cross Correlation of Real Output with: x_{t-4}	x_{t-3}	x_{t-2}	x_{t-1}	x_t	x_{t+1}	x_{t+2}	x_{t+3}	x_{t+4}
Output	1.29	.16	.25	.41	.66	**1.00**	.66	.41	.25	.16
Consumption:										
Market	.55	.05	.16	.34	.61	**.97**	.75	.55	.38	.24
Home	.91	.07	.14	.24	.38	**.56**	.43	.29	.17	.05
Aggregated	.63	.07	.17	.32	.54	**.83**	.64	.45	.29	.15
Investment:										
Market	4.79	.22	.30	.44	.64	**.86**	.63	.39	.10	−.26
Home	3.82	.13	.17	.29	.49	**.80**	.39	.18	.21	.50
Total	3.59	.21	.29	.43	.67	**.99**	.61	.34	.18	.12
Hours:										
Market	.52	.24	.31	.45	.67	**.98**	.58	.30	.14	.10
Home	.25	−.24	−.30	−.45	−.67	**−.98**	−.58	−.29	−.14	−.10
Total	.18	.24	.31	.45	.67	**.98**	.58	.29	.14	.10
Capital:										
Market	.51	−.41	−.36	−.28	−.12	**−.02**	.16	.45	.83	.63
Home	.29	−.42	−.35	−.23	−.05	**.25**	.38	.43	.49	.66
Total	.36	−.47	−.44	−.38	−.27	**−.09**	.10	.27	.47	.74
Productivity	.79	.11	.21	.38	.64	**.99**	.71	.48	.31	.20

the baseline home production model predicts that investment is *out of phase* relative to the U.S. data.

A. *Reintroducing Time to Build*

As stated in Section III, the time-to-build version of the baseline model has a time to build for market investment of four quarters and a standard time to build for home investment of one quarter. Business cycle moments for this model are contained in tables 4 and 5. Regarding the business cycle behavior of the two investment series, two results stand out. First, the correlation between home and market investment matches that observed in the U.S. data (see table 5). Second, home investment is now coincident to leading (the U.S. data display a lead of one quarter), whereas market investment is coincident with the cycle (the U.S. data display a lag of one quarter). In both regards, the time-to-build version of the model more closely conforms with the U.S. data than the baseline model with household production only.

Figure 1, which plots the response of output and the two investment series to a one-standard-deviation innovation to the market shock, clearly demonstrates why time to build makes such a difference with respect

TABLE 5
Model Comparisons

Model	Correlation	Standard Deviation	x_{t-4}	x_{t-3}	x_{t-2}	x_{t-1}	x_t	x_{t+1}	x_{t+2}	x_{t+3}	x_{t+4}
			Cross Correlation of Real Output with:								
U.S. data	.41	4.73	−.14	.04	.29	.56	**.80**	.87	.82	.68	.46
		6.74	.47	.61	.74	.80	**.76**	.52	.24	−.03	−.25
Baseline model	−.10	7.45	.19	.32	.46	.64	**.78**	.16	.03	−.05	−.11
		4.58	−.02	.07	.19	.33	**.53**	.96	.66	.40	.21
Baseline model TTB	.41	4.79	.22	.30	.44	.64	**.86**	.63	.39	.10	−.26
		3.82	.13	.17	.29	.49	**.80**	.39	.18	.21	.50
Benhabib et al. model	−.87	23.02	.15	.22	.30	.41	**.24**	−.09	−.10	−.11	−.11
		20.51	−.09	−.10	−.10	−.13	**.13**	.35	.25	.18	.12
Benhabib et al. model TTB	−.76	10.30	.33	.24	.25	.30	**.26**	.21	.12	−.04	−.23
		11.56	−.18	−.07	−.00	.11	**.37**	.17	.09	.15	.29
McGrattan et al. model	−.82	16.25	.18	.26	.37	.50	**.46**	−.10	−.12	−.14	−.14
		12.74	−.10	−.10	−.09	−.10	**.08**	.55	.40	.28	.18
McGrattan et al. model TTB	−.59	8.40	.33	.32	.39	.51	**.59**	.36	.15	−.09	−.39
		7.19	−.10	−.07	−.03	.05	**.28**	.16	.16	.31	.62
Greenwood-Hercowitz model	.37	5.25	.13	.26	.43	.64	**.86**	.62	.38	.18	.03
		3.97	.14	.25	.39	.54	**.77**	.44	.24	.09	−.03
Greenwood-Hercowitz model TTB	.23	3.71	.02	.12	.25	.45	**.71**	.81	.74	.55	.23
		5.21	.15	.22	.36	.57	**.83**	.26	−.10	−.23	−.17

Note.—The suffix TTB to a model denotes the time-to-build version of that model. The correlation column refers to the correlation between market and home investment. For *each* model, the first row of leads and lags with output pertains to market investment and the second pertains to home investment.

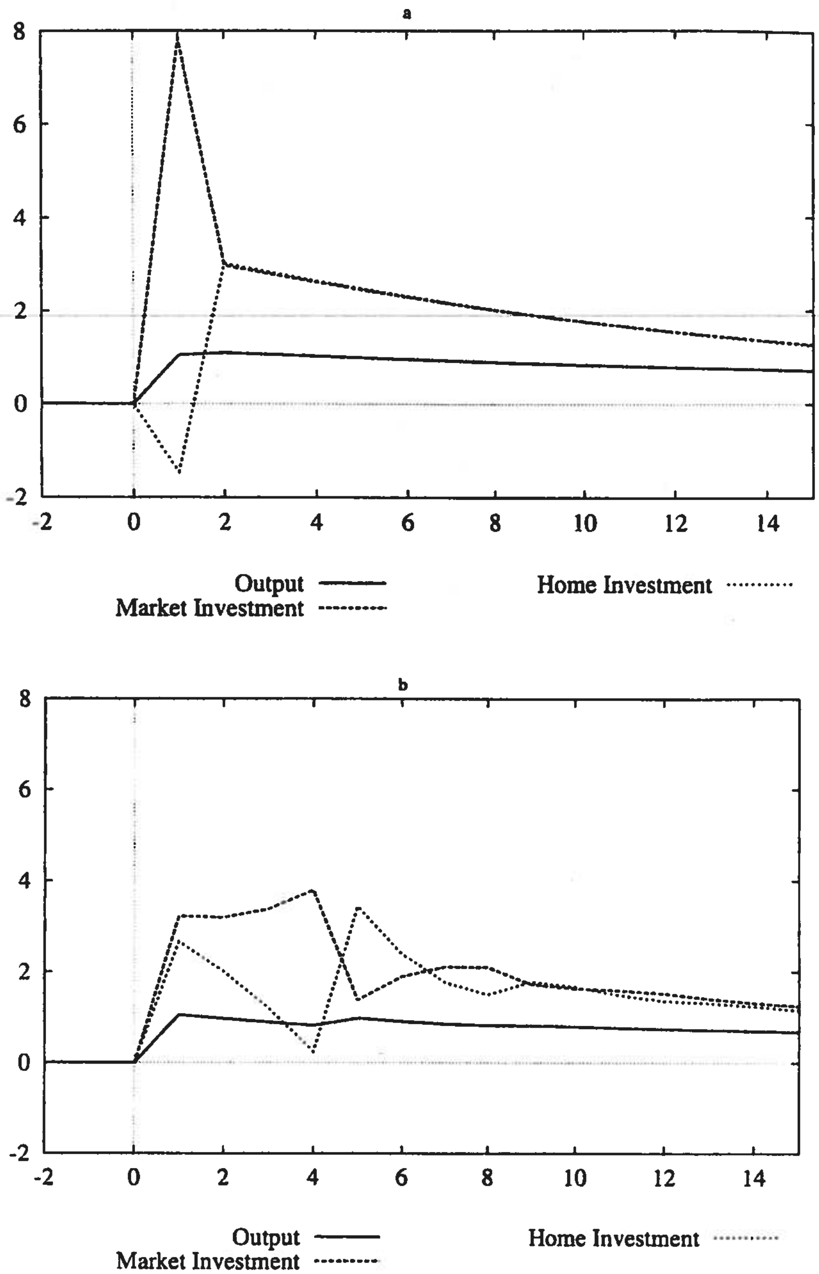

FIG. 1.—Response of investment to a market shock. *a*, Home production only. *b*, Home production with time to build.

to the behavior of the investment series.[8] For the baseline household production model, the immediate response is for the two investment series to move in opposite directions. The reason for this is the production asymmetry assumed in all home production models: market output can be used to augment the home capital stock, but home output can be used only as home consumption. Consequently, on impact the market capital stock is built up in order to produce more future output, which is then used to build up the home capital stock. The initial increase in market investment occurs at the cost of lower home investment. Only in subsequent periods do the two investment series move in tandem.

The effect of time to build is to mute the impact effect of the shock on market investment by drawing out the response over the four quarters it takes to build market capital. The smaller impact effect results from the fact that initiating a market investment project in the current period requires only one-fourth of the total resources used by the project. As a result, home investment need not take such a big hit in the initial period of the shock. In fact, as seen in figure 1, the parameterization for the baseline time-to-build model implies that home investment *rises* on impact, with diminishing effects in the three subsequent quarters as subsequent market investment projects are initiated. Intuitively, time to build reduces the cost, in terms of consumption and leisure, of market investment, thereby permitting greater home investment.

There are those who argue that time to build operates in much the same fashion as adjustment costs. Chang (2000) introduces into a home production model adjustment costs for market and home capital. He finds that adjustment costs can generate plausible volatility in the investment series and a positive correlation between the two. Chang does not report lead-lag patterns. When we add adjustment costs to market investment (only), we likewise find a positive correlation between the two investment series. However, like the basic home production model, this model predicts that market investment is coincident to leading, whereas home investment lags the cycle by a quarter.

B. Other Home Production Models Meet Time to Build

This section analyzes how incorporating time to build affects the results of the models discussed in the Introduction, namely, Benhabib et al. (1991) and Greenwood and Hercowitz (1991), as well as McGrattan et al. (1997). The business cycle properties of market and home investment

[8] Responses to the home shock are not presented because, as mentioned in Sec. III, the baseline parameterization implies that these variables do not respond to the home shock.

for each of these models, along with the U.S. data and the baseline model, are summarized in table 5.

The Benhabib et al. (1991) specification corresponds to $\xi = \frac{2}{3}$ (increased substitutability between market and home consumption), with all other parameters calibrated as in Section III. It should not be too surprising that without time to build, this model shares many of the same deficiencies as the baseline home production model. In particular, the investment series are out of phase relative to the data, and the two investment series are strongly negatively correlated. Furthermore, the volatility of the individual investment series is grossly counterfactual. Adding time to build to the Benhabib et al. specification has the following effects: (1) it lessens the negative correlation between home and market investment, (2) it reduces the volatility of both these series, and (3) home investment is now coincident with the cycle whereas market investment still leads. While not as successful as the baseline model, time to build nonetheless improves the coherence between the Benhabib et al. model and the U.S. data.

The McGrattan et al. (1997) model is more or less an estimated version of the Benhabib et al. (1991) model. In this case, $\xi = 0.4$ (still more substitutability between market and home consumption than in the baseline model), and $\text{corr}(\epsilon_{Mt}, \epsilon_{Ht}) = 0$ (the innovations to the market and home shocks are uncorrelated). Qualitatively, this model's performance is quite similar to that of the previous model—at least in regard to the cyclical behavior of the investment series. As above, adding time to build brings the investment volatilities closer to the data and lessens the negative correlation between the investment series. As well, market and home investment are both coincident with the cycle. Once more, time to build brings the model closer to matching U.S. business cycle experience.

Our parameterization of Greenwood and Hercowitz (1991) nearly matches that in Greenwood et al. (1995). Specifically, $\xi = \frac{2}{3}$, $\zeta = -\frac{1}{2}$ (implying greater complementarity between home capital and labor than is present in the baseline model), and $\text{corr}(\epsilon_{Mt}, \epsilon_{Ht}) = .995$, which implies that the market and home shocks (z_{Mt} and z_{Ht}) will be nearly perfectly correlated. Relative to the other straight home production models, the Greenwood and Hercowitz specification performs quite well with regard to the cyclical behavior of home and market investment. For example, the correlation between these series nearly matches the U.S. data, and the investment volatilities are close to the data, as is their phase pattern (market investment is coincident with the cycle rather than lagging, whereas home investment is coincident to leading as opposed to a definite lead in the data). Adding time to build worsens the correlation between home and market investment slightly. However, this is the only model that matches the lag in market investment seen in

TABLE 6
SENSITIVITY ANALYSIS

Model	Correlation	Standard Deviation	Cross Correlation of Real Output with: x_{t-4}	x_{t-3}	x_{t-2}	x_{t-1}	x_t	x_{t+1}	x_{t+2}	x_{t+3}	x_{t+4}
U.S. data	.41	4.73	−.14	.04	.29	.56	.80	.87	.82	.68	.46
		6.74	.47	.61	.74	.80	.76	.52	.24	−.03	−.25
Baseline model only	−.10	7.45	.19	.32	.46	.64	.78	.16	.03	−.05	−.11
		4.58	−.02	.07	.19	.33	.53	.96	.66	.40	.21
Baseline model TTB	.41	4.79	.22	.30	.44	.64	.86	.63	.39	.10	−.26
		3.82	.13	.17	.29	.49	.80	.39	.18	.21	.50
$\gamma = 2$	.13	6.19	.18	.31	.46	.65	.83	.26	.11	.01	−.08
		3.63	−.00	.11	.25	.43	.65	.95	.65	.40	.20
$\gamma = 2$, TTB	.46	4.44	.19	.28	.43	.63	.87	.67	.43	.16	−.20
		3.50	.12	.18	.31	.53	.83	.39	.16	.17	.41
$\beta = .99$	.10	7.37	.18	.31	.47	.66	.83	.23	.09	−.01	−.09
		4.21	−.00	.10	.24	.40	.62	.98	.67	.40	.20
$\beta = .99$, TTB	.49	5.06	.19	.29	.43	.64	.89	.68	.44	.16	−.21
		3.99	.14	.19	.31	.52	.83	.38	.14	.15	.42
$\tau_K = .50$	−.60	12.71	.19	.29	.41	.56	.61	−.05	−.11	−.13	−.16
		8.69	−.08	−.04	.02	.08	.25	.81	.58	.37	.22
$\tau_K = .50$, TTB	.07	6.75	.27	.33	.45	.62	.80	.53	.26	−.03	−.39
		4.65	.05	.09	.19	.36	.64	.38	.27	.38	.72

NOTE.—The suffix TTB on a model denotes the time-to-build version of that model. γ refers to the coefficient of relative risk aversion, β refers to the discount factor, and τ_K refers to the tax rate on capital income. The correlation column refers to the correlation between market and home investment. For *each* model, the first row of leads and lags with output pertains to market investment and the second pertains to home investment.

the data. Furthermore, the other home production models tend to predict that market investment is more volatile than home investment, whereas the opposite is true in the data; an exception is the original Greenwood and Hercowitz specification. Adding time to build to our version of the Greenwood and Hercowitz model helps on this dimension as well.

C. *Sensitivity Analysis*

The results of a further set of experiments are summarized in table 6. In particular, we explore the sensitivity of our results to a higher coefficient of relative risk aversion ($\gamma = 2$), a higher discount factor ($\beta = 0.99$), and a lower tax rate on capital income ($\tau_K = 0.50$). Qualitatively, the results for each experiment are quite similar to those seen for the baseline model. In particular, time to build has the following effects: (1) it improves the correlation between market and home investment, and (2) it brings the phase pattern of both investment series closer to that seen in the data. These results suggest that the improvements obtained by adding time to build to the baseline model are fairly general and are not artifacts of a judicious choice of parameter values.

V. Conclusion

The standard home production model makes two counterfactual predictions: (1) Market and home investment are negatively correlated, whereas the data exhibit a positive correlation. (2) Market and home investment are out of phase relative to the data. On this second point, in the data, market investment lags the cycle by about one quarter, whereas the basic home production model predicts that market investment is coincident to leading; in the data, home investment leads the cycle, whereas the model predicts a lagging pattern. These anomalies are largely resolved when time to build is added to the home production model. In particular, adding time to build produces a positive correlation between market and home investment (for our parameterization, it actually matches the U.S. data) and brings the phase pattern of the investment series more closely in line with the data. The slight leading pattern of market investment in the baseline home production model is coincident under time to build, whereas the lagging behavior of home investment becomes coincident to leading. The parameterization is otherwise standard. Specifically, the home production function is Cobb-Douglas, as is the aggregator of market and home consumption. Kydland (1995) argued that any deviation from Cobb-Douglas is difficult to reconcile in the face of key balanced growth facts, in particular, the secular decline in the price of durables relative to nondurables and the constant expenditure share of durables.

The successes of existing home production models have come at a high cost. For example, Benhabib et al. (1991) emphasize the role of household production in generating procyclical movement in the labor input in different sectors. This and other modest improvements in business cycle behavior are bought at the cost of the anomalies listed above. Further, as shown in table 5, the volatility of market and home investment is grossly at variance with the data. Much the same can be said of McGrattan et al. (1997). As discussed in Section IV*B*, adding time to build to these models moves each of them to greater conformance with the observed cyclical properties of market and home investment. Although the Greenwood and Hercowitz (1991) model has fewer problems—at least with regard to the cyclical pattern of the investment series—even here time to build makes positive contributions.

Appendix

Data Sources

The data series (and their Haver analytics mnemonic in parentheses) are as follows: gross domestic product (GDPH); for consumption, nondurables (CNH), services (CSH), housing services (CSRH), and durables (CDH); private nonresidential fixed investment (FNH); private residential fixed investment (FRH); and hours (LHTPRIVA).

All data are quarterly and seasonally adjusted at annual rates. Apart from hours, all data are in real chained 1992 dollars. Hours corresponds to the Bureau of Labor Statistics aggregate hours of private nonagricultural wage and salary workers. Consumption = nondurables + services − housing services; market investment = private nonresidential fixed investment; household investment = durables + private residential fixed investment; productivity = gross domestic product ÷ hours.

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