Generation-3 Monetary Search Models

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Introduction

- So far we have seen models where money was indivisible.

- This introduced various constraints on the environment:
  - agents could hold only 1 unit of money;
  - had to always trade goods and money one-for-one;
  - could not hold goods and money simultaneously;
  - artificial link between money supply and the number of agents holding money.

- We now allow money to be divisible. A nontrivial issue: how to deal with the distribution of money holdings across agents.

- Two papers: Shi (*Econometrica*, 1997); Lagos and Wright (*JPE*, 2005).

I. "A Divisible Search Model of Fiat Money", Shi (1997)

- Make money divisible.
- Sever the link between money supply and the number of agents who hold money.
- Getting around the distribution: assume each household consists of a continuum (measure 1) of members who pool money and consumption.
- Examine neutrality and superneutrality properties of money (money will be neutral, but not superneutral).
- Study an extension with endogenous choice of the share of money holders.

Basic Model: Environment

- Discrete time
- Continuum of perishable goods: circle of circumference 2.
- Intrinsically worthless storable object: money. Perfectly divisible, can trade any fraction of it.
- A continuum of households of measure 1. Each household consists of continuum of measure 1.
- All household members share the same consumption.

The Household

- An exogenous share N of household members are given money. Money holders do not produce.
- A_i is the set of money holders in household i; A_i^c is the set of producers within same household.
- Specialization: each household consumes, with equal utility, a subset of goods along the arc on the circle of length $z \in [0, 1]$. Consumption set: $D_i = \{j : ji \leq z\}$
- Utility of consuming q units of any good in D_i is $u(q) = aq$, $a > 0$.
- Production good: determined by random shocks - each period, a good i^* is selected uniformly and independently for i to produce. Production cost: $\phi(q)$, usual assumptions.
- Agents never consume their own production good.

Timing

Within any period:

1. Production shock realizes.
2. Household divides money balances evenly among its money holders.
3. Each member of the household is randomly matched to one agent from another household.
4. Matched agents decide whether to trade: can barter or trade for money.
5. Terms of trade are determined by bargaining.
6. Post-exchange, agents bring receipts back to the household; hh allocates goods evenly among members for consumption.
7. Household receives a lump-sum transfer $\tau_{t+1} = (\gamma - 1)M_t$; γ - constant gross rate of money growth.

Distribution of Matches

- No aggregate uncertainty.

- Idiosyncratic uncertainty: each individual agent is unsure of what match he will be in. At household level, distribution of matches is a.s. nonrandom.

- z captures the probability of single coincidence of wants.

- z^2 = probability of double coincidence of wants.

Household Decision Problem

- Suppose a member j of household i meets member $-j$ of household $-i$.

- Two types of matches result in trade: barter or money-for-goods (goods-for-money).

- Let $I_b = \{j \in A_i^c : -j \in A_i^c, i^* \in D_{-i}, -i^* \in D_i\}$. I_b has measure $z^2(1-N)^2$.
- $I_p = \{j \in A_i^c : -j \in A_{-i}, i^* \in D_{-i}\}$. I_p has measure $zN(1-N)$.
- $I_m = \{j \in A_i : -j \in A_{-i}^c, -i^* \in D_i\}$. I_m has measure $zN(1-N)$.

Household Decision Problem

Choose consumption and money holdings, taking terms of trade in the economy as given $(\hat{q}^m, \hat{q}^b, \hat{L})$:

$$\begin{aligned}
\max_{C_{it}, M_{it+1}} \quad & \sum_{t=0}^{\infty} \beta^t (u(C_{it}) - \Phi_{it}) \\
\text{s.t. } C_{it} &\leq \int_{j \in I_{mt}} \hat{q}_t^m(-j)dj + \int_{j \in I_{bt}} \hat{q}_t^b(-j)dj \equiv Y_{it} \\
\Phi_{it} &= \int_{j \in I_{pt}} \phi(\hat{q}_t^m(j))dj + \int_{j \in I_{bt}} \phi(\hat{q}_t^b(j))dj \\
M_{it+1} &= M_{it} + \tau_{t+1} + \int_{j \in I_{pt}} \hat{L}_t(-j)dj - \int_{j \in I_{mt}} \hat{L}_t(j)dj \\
\hat{L}_t(j) &\leq M_{it}/N, \forall j \in I_{mt}
\end{aligned}$$

Cannot get money from other household members during trading.

Household Decision Problem

- No aggregate risk $\Rightarrow$ the household maximization problem has no uncertainty (integrate out idiosyncratic risk).
- In this deterministic setup, we do not have to keep track of inventory distributions of money: only of the variable M - the total amount of money in the household. (Among individuals, always have a nontrivial distribution).
- $C_{it} = Y_{it}$.
- With ω_{it} and λ_{it} as the relevant Lagrange multipliers, have

$$\begin{aligned} \omega_{it} &= \beta \left[\omega_{it+1} + \frac{1}{N} \int_{j \in I_{mt+1}} \lambda_{it+1}(j) dj \right] \\ 0 &= \lambda_{it}(j)[M_{it}/N - L_{it}(j)], \forall j \in I_{mt} \end{aligned}$$

Bargaining: Barter Match

- An agent in a bilateral match takes as given economy-wide variables, as he bargains over the terms of trade of his match.

- A barter match involves two symmetric agents: bargaining power = 1/2.

- The match solves

$$\max_{q_i^b, q_{-i}^b} \left[a q_{-i}^b - \phi(q_i^b) \right]^{1/2} \left[a q_i^b - \phi(q_{-i}^b) \right]^{1/2}$$

- Solved by $q_i^b = q_{i-}^b = \bar{q} = \phi'^{-1}(a)$. Ex-post efficient quantities traded.

Bargaining: Monetary Match

- Money holder pays L_i for q^m_{-i}.
- Solve

$$\max_{L_i, q^m_{-i}} \left[a q^m_{-i} - (\omega_i + \lambda_i) L_i\right]^{\theta} \left[\omega_{-i} L_i - \phi(q^m_{-i})\right]^{(1-\theta)}$$

- First-order conditions:

$$\begin{aligned} \phi'(q^m_{-i}) &= \frac{a\omega_{-i}}{\omega_i + \lambda_i} \\ L_i &= \frac{\theta\phi(q^m_{-1} + (1-\theta) q^m_{-i} \phi'(q^m_{-i})}{\omega_{-i}} \end{aligned}$$

- FOC-L implies that $q^m < \bar{q}$ in symmetric eq'm.
- Observe that threat points in the problem are endogenous: functions of ω_i, ω_{-i} and λ_i, i.e. relative scarcity of goods and money in the market affect bargaining outcome.

Equilibria

- There always exists a nonmonetary equilibrium $q^m = \hat{q}^m = 0$, self-fulfilling.

- There exists a continuum of "nonbinding" monetary equilibria where $\lambda = 0$. There, $q^m = q^b = \bar{q}$, $\omega_t = \beta\omega_{t+1}$, and nominal price of goods L/q^m falls over time at rate $1 - \beta$. Self-fulfilling bubbles on money: agents keep increasing proportions of their money holdings as store of wealth because they expect money value to increase. Less money in trade, so value continues to increase. Self-fulfilling.

- We focus on symmetric "binding" monetary equilibrium.

Symmetric Binding Monetary Equilibrium

A symmetric monetary equilibrium is a collection of variables for each t, $\{C_{it}, M_{it}, \omega_{it}, \lambda_{it}, L_t, q_t^b, q_t^m, \hat{L}_t, \hat{q}_t^b, \hat{q}_t^m\}$, such that:

1. $C_{it} = C_t$, $M_{it} = M_t$, $\omega_{it} = \omega_t$, $\lambda_{it} = \lambda_t$ $\forall i$, and $\lambda(j) = \lambda(j')$ for all $j, j' \in I_{mt}$;

2. (C_{it}, M_{it}) solve household problem taking market terms of trade as given;

3. $(L_{it}, q_{it}^b, q_{it}^m)$ solve the appropriate bargaining problems taking C, M, λ, ω as given, and $(\hat{L}_t, \hat{q_t^b}, \hat{q_t^m}) = (L_{it}, q_{it}^b, q_{it}^m)$ for all i;

4. $M_t = \hat{M}_t$.

Characterization

The symmetric binding monetary equilibrium is characterized by (omit time subscripts):

$$\begin{aligned} C &= z(1-N)(Nq^m + z(1-N)\bar{q}) \qquad (1) \\ \Phi &= z(1-N)(N\phi(q^m) + z(1-N)\phi(\bar{q})) \\ M' &= M + \tau = \gamma M \end{aligned}$$

$$\begin{aligned} \lambda &= \left(\frac{a}{\phi'(q^m)} - 1\right)\omega \qquad (2) \\ L &= M/N \qquad (3) \\ \omega &= \frac{N(\theta\phi(q^m) + (1-\theta)q^m\phi'(q^m))}{M} \qquad (4) \end{aligned}$$

and

$$q^m = G(q'^m), \qquad (5)$$

with $G(q)$ defined in the text.

Characterization

- The solution to (5) is the key to the existence of monetary steady state that is binding.
- *The binding monetary steady state q^* exists iff $\gamma > \beta$, and if so, it is given by*

$$\phi'(q^*) = \alpha \left(1 + \frac{\gamma/\beta - 1}{z(1-N)}\right)^{-1}.$$

- q is the real money balance transacted in the monetary trade.
- From (5), an increase of the rate of growth of money γ decreases real balances q (produces offer fewer units of goods because money is losing value).
- This is *super nonneutrality*: money growth reduces output and consumption in the economy. Can show $\gamma = \beta$ is optimal: Friedman rule.

Extension with Endogenous N

- A binding steady state exists only if double coincidence of wants is unlikely, $z < \theta$, and money growth rate is moderate.

- Both neutrality and superneutrality of money are maintained.

- Now, in equilibrium, share of money holders is inefficiently low, because households ignore an externality that they impose (decision on N affects trading opportunities for all). So if γ is low to start, increasing it will cause household to give money to more members (to trade it away faster), thus increasing the average trading opportunity.

Conclusions

- Many details of extensions omitted.
- This was the first paper to allow money to be divisible.
- By disentangling money supply and the number of people holding money, we can speak meaningfully about the effects of money growth, analyzing neutrality properties of money.
- Advantage: analytically tractable, despite underlying distributions of money.
- Next: we look at a different way of dealing with the same issue.

II. Lagos and Wright, JPE 2005

- Another way of having money be divisible while preserving tractability.

- Idea: quasilinearity in the utility function eliminates wealth effect of money demand.

- Result: degenerate distribution of money holdings.

- Quantitatively evaluates the welfare cost of inflation.

Environment

- Discrete time. [0,1] continuum of infinitely-lived agents.
- Two subperiods: decentralized market (DM) and centralized market (CM).
- In DM, agents trade after matching bilaterally, with probability α, randomly and anonymously.
- Goods in DM are specialized: each agent consumes a subset of the goods, and can produce a good he cannot himself consume.
- Probability of a double-coincidence: δ. Probability of a single coincidence: σ.

Environment

- CM: Walrasian market. Consumption good is a general good (could be specialized - does not matter).

- Goods nonstorable and perfectly divisible; money m is storable and perfectly divisible.

- Constant money supply: M

- In DM, either barter or monetary exchange is possible.

- In both markets, all agents can produce by converting labor into goods one-for-one.

Environment

- Preferences are given by:
  $\mathcal{U}(q,h,X,H) = u(q) - c(h) + U(X) - H$

- q, h refer to DM consumption and labor; X and H refer to CM consumption and labor.

- $u' > 0$, $c' > 0$, $U' > 0$, $u'' < 0$, $c'' \geq 0$, $U'' \leq 0$.

- More generally, can have linearity on CM consumption rather than labor.

Agent's Problem

- $F(\tilde{m})$ - measure of agents starting DM holding $m \leq \tilde{m}$. $G(\tilde{m})$ - same for CM.

- Initial distribution F_0 is given exogenously.

- $\int m dF(m) = \int m dG(m) = M$

- No uncertainty except the nature of match in DM.

Decentralized Market

- Notation: $V(m)$ - value function in DM, $W(m)$ - value function in CM; $q(m,\tilde{m})$, $d(m,\tilde{m})$ - consumption and money traded in a monetary meeting; $B(m,\tilde{m})$ - payoff in double-coincidence meetings.

$$
\begin{aligned}
V(m) &= \alpha\sigma \int \left[u(q(m,\tilde{m})) + W(m - d(m,\tilde{m})) \right] dF(\tilde{m}) \\
&+ \alpha\sigma \int \left[-c(q(\tilde{m},m)) + W(m + d(\tilde{m},m)) \right] dF(\tilde{m}) \\
&+ \alpha\delta \int B(m,\tilde{m}) dF(\tilde{m}) + (1 - 2\alpha\sigma - \alpha\delta) W(m)
\end{aligned}
$$

Centralized Market

$$
\begin{aligned}
W(m) &= \max_{X,H,m'} \{U(X) - H + \beta V(m')\} \\
\text{s.t. } X &= H + \phi m - \phi' \\
X &\geq 0 \\
H &\in [0, \bar{H}] \\
m' &\geq 0
\end{aligned}
$$

First, solve problem under assumption of interiority (H may pose problems), then check that H is interior.

Double-Coincidence Meeting

- Symmetric Nash problem, as in Trejos and Wright (2005).
- Threat points given by continuation values $W(m)$.
- Result: money holdings do not affect the terms of trade. $q = q^*$ where $u'(q^*) = c'(q^*)$
- $B(m, \tilde{m}) = u(q^*) - c(q^*) + W(m)$.

Monetary Meeting: Bargaining Problem

$$\max_{q,d}[u(q)+W(m-d)-W(m)]^{\theta}[-c(q)+W(\tilde{m}+d)-W(\tilde{m})]^{1-\theta}$$

$$\begin{aligned} \text{s.t. } d &\leq m \\ q &\geq 0 \end{aligned}$$

- Threat points are continuation values.
- θ is bargaining weight of buyer. $\theta = 1$ is "buyer take all".

Equilibrium

A monetary equilibrium is a list $\{V, W, X, H, m', q, d, \phi, F, G\}$ such that, for all t:

- $V(m)$ and $W(m)$ are value functions and $X(m), H(m), m'(m)$ are decision rules that, given prices and distributions, solve the agent problems in the CM and the value function condition in the DM;
- $q(m, \tilde{m})$ and $d(m, \tilde{m})$ are the terms of trade that solve the bargaining problem, given the value functions;
- $\phi > 0$;
- Money market clears: $\int m'(m)dG(m) = M$
- F, G are consistent with intitial conditions and evolution of money holdings.

CM Problem

Substituting the budget constraint in:

$$W(m) = \phi m + \max_{X,m'} \{U(X) - X - \phi m' + \beta V(m')\}$$

Claims:

- $X(m) = X^*$.
- $m'(m)$ does not depend on m.
- W is linear in m with slope ϕ.

Bargaining Solution

Problem simplifies thanks to linearity:

$$\begin{aligned} \max_{q,d} \quad & [u(q) - \phi d]^{\theta}[-c(q) + \phi d]^{1-\theta} \\ \text{s.t. } d &\leq m \\ q &\geq 0 \end{aligned}$$

Solution:

$$q(m, \tilde{m}) = \begin{cases} \hat{q}(m) & \text{if } m < m^* \\ q^* & \text{if } m \geq m^* \end{cases} \quad \text{and } d(m, \tilde{m}) = \begin{cases} m & \text{if } m < m^* \\ m^* & \text{if } m \geq m^* \end{cases}$$

where $\hat{q}(m)$ solves

$$z(q) = \frac{\theta c(q) u'(q) + (1-\theta) u(q) c'(q)}{\theta u'(q) + (1-\theta) c'(q)}$$

Bargaining Solution

- d and q only depend on buyer's money holdings, not on seller's.
- Buyer gets the efficient quantity q^* if he has at least m^* in cash.
- Can show that $q(m)$ is strictly increasing for $m < m^*$, so that $q < q^*$ for any $m < m^*$.

Equilibria

- Substitute results into $V(m)$:

$$V(m) = v(m) + \phi m + \max_{m'}\{-\phi m + \beta V(m')\}$$

where

$$\begin{aligned} v(m) &= \alpha\sigma[u(q) - \phi d] + \alpha\sigma \int [\phi d - c(q)] dF(\tilde{m}) \\ &+ \alpha\delta(u(q^*) - c(q^*)) + U(X^*) - X^* \end{aligned}$$

Equilibria

- Can show that any equilibrium must satisfy $\phi \geq \beta\phi'$ - puts a lower bound on admissible inflation ϕ/ϕ' of β (Friedman rule).
- Can show that unless $\beta = \phi m'$ and $\theta = 1$, in equilibrium, $m < m^*$ always, so that $q < q^*$. Compare to Kiyotaki and Wright (1993) and Trejos and Wright (1995). Different intuition: *holdup* problem.
- Uniqueness of equilibria: guaranteed if $\theta \approx 1$, or if u' is log-concave. Shown by checking second-order conditions.
- In equilibrium, distribution F is degenerate: $m' = M$.
- Can reduce the solution of q to a difference equation.

Welfare Cost of Inflation

- The model is parameterized to study its properties in quantitative examples.
- Parameters chosen to match properties of money demand in the data, but some parameters (e.g. θ) are hard to pin down.
- Measure of cost of inflation: how much would agents be willing to give up in terms of consumption to have inflation 0 rather than τ.
- The cost of 10% inflation is thus estimated to be between 3 and 5% of consumption - a higher estimate than previous numbers (Lucas, 2000 - $< 1\%$), suggesting that modeling frictions explicitly matters.

III. Other Possibilities: Rocheteau and Wright (2004; Econometrica, 2005)

- The basic model sets up the bilateral matching sector (decentralized market) with bargaining in the meetings.

- Need not be the case.

- Recall that the *holdup problem* played an important role in the bargaining sector: worth exloring what happens in other settings.

- Implications both for theoretical and quantitative results.

Three Decentralized Market Setups

1. Like in Lagos and Wright (2005), with bargaining: *search eqiulibrium.*

2. Walrasian markets (price taking), with limited participation: *competitive equilibrium.*

3. Partially directed search (price posting): *competitive search equilibrium.*

Environment

- As in LW, two markets co-exist in the economy (happen sequentially in each period): centralized (CM) and decentralized (DM). Role: (a) tractability of the model (collapsing the distribution of money holdings); (b) integration of "mainstream" Walrasian macro setup with frictional trade.
- In the CM, everyone can produce and consume frictionlessly.
- In the DM, some frictions always assure that money is essential: anonymity of agents, uncertain meetings, absence of double-coincidence of wants.
- Here, unlike LW, everyone knows whether they will be a buyer or a seller in DM ahead of time (types predetermined exogenously).

Centralized Market: Same in All Models

Buyer:

$$\begin{aligned} W^b(z^b) &= \max_{\hat{z},x,y}\{U(x) - y + \beta_1 V^b(\hat{z})\} \\ \text{s.t. } \hat{z} + x &= z^b + T + y \end{aligned}$$

Seller:

$$\begin{aligned} W^s(z^s) &= \max_{\hat{z},x,y}\{U(x) - y + \beta_1 \max\left\{V^s(\hat{z}), \beta_2 W^s\left(\frac{\hat{z}}{\gamma}\right)\right\} \\ \text{s.t. } \hat{z} + x &= z^s + y \end{aligned}$$

- WLOG, money transfers given only to buyers.
- Sellers get to enter DM with some probability < 1 (share n); consider two cases - where n is exogenous, and where sellers choose entry endogenously.

(a) Search DM and Equilibrium

- Buyers spend all of their money. Terms of trade do not depend on sellers' money holdings. Sellers choose $\hat{z} = 0$ - different from LW, because here they know they will be sellers in advance.

- With exogenous n, a monetary equilibrium exists and is unique. With n endogenous (free entry), equilibria exist for moderate money growth rate γ, generically not unique, except at Friedman Rule $\gamma = \beta$.

- Equilibria are *inefficient* in general. With n exogenous, Friedman rule is optimal. Friedman rule together with $\theta = 1$ deliver efficiency of equilibrium as well.

- With free entry, Friedman rule is optimal, but it cannot deliver efficiency in equilibrium ever. (Because if $\theta = 1$ then $n = 0$).

(b) Competitive DM (Price Taking)

- Suppose a Walrasian auctioneer in DM.

- Can still have money be essential: assume agents are anonymous and there is a double-coincidence problem, and assume limited participation (not all agents get in) to have search-type frictions.

- Let $\alpha_b(n)$ and $\alpha_s(n)$ be the probability for buyer (resp. seller) of getting into the DM.

- Buyers and sellers who get into the market see the (real) price of DM goods p, and choose demand and supply q^b and q^s accordingly.

DM Value Functions

$$
\begin{aligned}
V^b(z^b) &= \alpha_b(n) \max_{q^b} \left\{ u(q^b) + \beta_2 W^b \left(\frac{z^b - pq^b}{\gamma} \right) \right\} \\
&+ (1 - \alpha_b(n)) \beta_2 W^b \left(\frac{z^b}{\gamma} \right) \\
\text{s.t. } pq^b &\leq z^b
\end{aligned}
$$

$$
\begin{aligned}
V^s(z^s) &= \alpha_s(n) \max_{q^s} \left\{ -c(q^s) + \beta_2 W^s \left(\frac{z^s + pq^s}{\gamma} \right) \right\} \\
&+ (1 - \alpha_s(n)) \beta_2 W^s \left(\frac{z^s}{\gamma} \right) - k
\end{aligned}
$$

Competitive Equilibrium

- Buyer always spends all his money (brings just enough). Seller brings no money.

- With n exogenous, there is a unique competitive equilibrium. With free entry, equilibria exist for moderate money growth rate, generically not unique, except at Friedman rule.

- Friedman rule yields efficiency with exogenous n; Friedman rule and Hosios condition are necessary and sufficient for efficiency with free entry.

- Friedman rule is optimal with exogenous n. With free entry, in the absence of Hosios condition (which is not likely to hold), n is typically inefficient, and if it is too high, $\gamma > \beta$ is optimal.

Non-Optimality of the Friedman Rule

- From above, it is possible to have Friedman Rule not be optimal.
- Reason: when n is chosen endogenously, its choice carries externalities - a congestion effect for other sellers, and thick market effect for buyers.
- If congestion effect dominates, then n is too high; inflation is optimal because it reduces incentive to enter.
- Inflation also reduces q, so it does have a negative effect, but it is only second-order.

(c) Competitive Search DM

- At the beginning of the period, market makers (alt. buyers OR sellers) announce submarkets to be open in the DM, described by terms (q, d).
- Buyers and sellers choose which submarket to go to in the DM. By going, they commit to the posted terms of trade. Buyer/seller ratio in a submarket is given by n
- Partially directed search: agents choose which submarket to go to, but then still have to search to find a partner in that submarket. (Alternative: more or fewer buyers than a seller can accomodate may show up to a given seller).
- In equilibrium, the set of submarkets Ω, $\omega \in \Omega = \{q, d, n\}$ is complete: could not add additional ones that would make buyers or sellers better off.

DM Value Functions

$$V^b(z^b) = \max_{\omega} \left\{ \alpha(n)\mathbf{1}_{z^b \geq d} \left[u(q) + \beta_2 W^b \left(\frac{z^b - d}{\gamma} \right) \right] \right\} + (1 - \alpha(n)\mathbf{1}_{z^b \geq d})\beta_2 W^b \left(\frac{z^b}{\gamma} \right)$$

$$V^s(z^s) = \max_{\omega} \left\{ \frac{\alpha(n)}{n} \left[-c(q) + \beta_2 W^s \left(\frac{z^s + d}{\gamma} \right) \right] \right\} + \left(1 - \frac{\alpha(n)}{n} \right) \beta_2 W^b \left(\frac{z^s}{\gamma} \right) - k$$

In addition, must solve for (q, d, n) to maximize W^b subject to seller participation constraint - problem solved in CM.

Competitive Search Equilibrium

- Buyer always spends all his money (brings just enough). Seller brings no money.
- The definition of equilibrium here involves the set Ω with sets of market-maker choices conditional on submarket ω.
- With exogenous n, competitive equilibrium exists and is uniquely determined. With free entry, equilibrium exists for moderate money growth rates, and is generically unique.
- Friedman Rule is always optimal, and always implies efficiency and uniqueness of equilibrium. Idea: sellers and buyers get around the holdup problem because they contract in advance, and market makers internalize the externalities of the choice of n on arrival rates.

Quantitative Implications

What is the welfare cost of inflation? How much consumption would agents be willing to give up to go from 10% to 0% inflation?

- In search equilibrium, the cost can be between 3% and 5% of consumption, depending on calibration.
- In competitive search equilibrium, the cost is between 0.67% and 1.1% of consumption.
- In competitive equilibrium, the cost is around 1.54%.

⇒ Modeling frictions that give rise to money explicitly gives very different results, generally, than reduced-form models, but the exact specification of the frictions is also important.