Aggregate Implications of Lumpy Adjustment

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1. Motivation

Micro adjustment is lumpy for many aggregates of interest:

- stock of durable good
- nominal prices
- capital stock
- employment

Is this relevant for aggregate dynamics?

Investment:

- Yes ... in partial equilibrium: Caballero - Engel - Haltiwanger (1995), Cooper - Haltiwanger - Power (1999), Caballero - Engel (1999)
- No ... in general equilibrium: Thomas (2002), Khan - Thomas (2003, 2008)
- Yes ... in general equilibrium: This paper

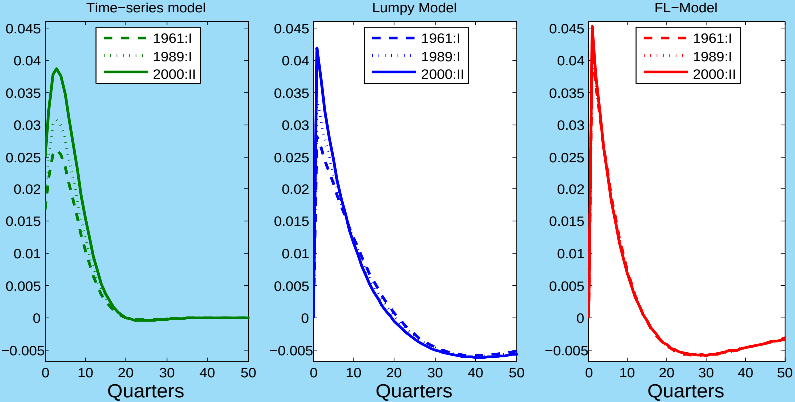
Relevant in what sense?

- Better micro foundations important per se
- Better match of the data
- Better out-of-sample forecasts
- Matters for relevant policy questions

In this paper:

- IRF with significant and systematic history dependence

In a nutshell

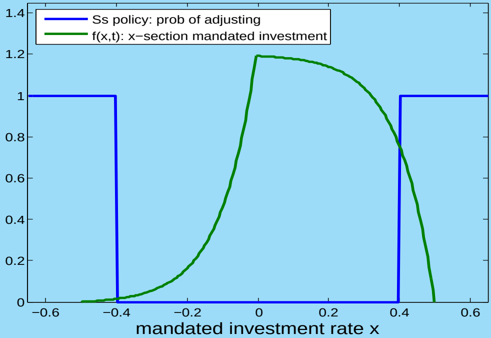


Outline

1. Motivation
2. Basic mechanism
3. Time series evidence
4. Model
5. Confronting the evidence
6. Aggregate dynamics
7. Conclusion

2. Basic mechanism

- Rationalize lumpy micro behavior via non-convex (fixed) adjustment costs
- Need to take heterogeneous firms seriously
- Main ingredients:
  - cross-section of mandated investment: $f(x)$
  - inaction range: $L \leq x \leq U$
- $f(x)$ and L, U depend on the state of the economy:
  - aggregate shocks
  - distribution of firm specific shocks
  - distribution of capital stock



$$
\begin{aligned}
\frac{I_t}{K_t} &\cong \int_U^{+\infty} |x| f(x,t)\,dx - \int_{-\infty}^{L} |x| f(x,t)\,dx \\
\mathrm{IRF}_{0,t} &\cong \underbrace{F(L) + (1 - F(U))}_{\text{intensive margin}} + \underbrace{|L| f(L) + U f(U)}_{\text{extensive margin}}
\end{aligned}
$$

Lumpy Investment and Time-Varying IRFs

After a sequence of above avge. shocks ('boom'):

- $f(x,t)$ with more mass close to upper trigger
- investment more responsive to a marginal shock

Similarly: investment less responsive during downturns,

Continuous time for a formal result

Beware of linear models when predicting the impact of a stimulus

To what an extent does this intuition extend to a fully specified DSGE model?

3. Time series evidence

- Let: $x_t \equiv I_t / K_{t-1}$
- Consider the following GARCH-type model:

$$
\begin{aligned}
x_t &= \sum_{j=1}^{p} \phi_j x_{t-j} + \sigma_t e_t, \\
\sigma_t &= h(x_{t-1}, x_{t-2}, \cdots),
\end{aligned}
$$

- It follows that:

$$\mathrm{IRF}_{0,t} = \frac{\partial x_t}{\partial \varepsilon_t} = \sigma_t = h(x_{t-1}, x_{t-2}, \cdots)$$

- Consider two specifications (also kernel estimators):

$$
\begin{aligned}
h(x_{t-1}, x_{t-2}, \cdots) &= \alpha_0 + \alpha_1 \bar{x}_{t-1}^k, \\
h(x_{t-1}, x_{t-2}, \cdots) &= (\tilde{\alpha}_0 + \tilde{\alpha}_1 \bar{x}_{t-1}^k)^2,
\end{aligned}
$$

with $\bar{x}_t^k \equiv \frac{1}{k} \sum_{j=1}^{k} x_{t-j}$.

Data:

- private, fixed, non-residential investment-to-capital-ratio
- quarterly, 1960.I–2005.IV, BLS

Series:	All	Equip	Str
p:	3	3	2
k:	8	7	3
$\alpha_1 \times 10^2$:	3.142	2.488	3.279
t-α_1:	2.588	2.254	4.123
one sided p-α_1:	0.005	0.013	0.000
$\pm\log(\sigma_{95}/\sigma_5)$:	0.505	0.468	0.895
$\pm\log(\sigma_{90}/\sigma_{10})$:	0.429	0.334	0.771
no. obs. est. p:	180	180	180
no. obs. est. k:	176	176	176

4. Model

- Incorporates lumpy investment (and therefore firm heterogeneity) into an otherwise standard stochastic growth model
- Producer side: interesting
- Household side: simple
- Follows closely Khan and Thomas (2008)
- Two differences:
  - sector specific productivity shocks
  - maintenance investment: necessary to continue operation (fraction χ of depreciated capital)

Production Units

- No entry or exit
- Aggregate, sectoral and idiosyncratic productivity shocks
- Unit's production function:

$$y_t = z_t \epsilon_{S,t} \epsilon_{I,t} k_t^{\theta} n_t^{\nu}.$$

  with log-AR(1) shocks
- $\theta + \nu < 1$
- I.i.d. cost of adjusting capital, ξ, drawn from a $U[0, \bar{\xi}]$, measured in units of labor

Production Units: Bellman Equation

Unit's problem:

$$V^1(\epsilon_S, \epsilon_I, k, \xi; z, \mu) = \max_n \{\mathrm{CF} + \max(V_i, \max_{k'}[-\mathrm{AC} + V_a])\},$$

where

$$\begin{aligned}
\mathrm{CF} &= [z\epsilon_S\epsilon_I k^\theta n^\nu - \omega(z,\mu)n - i^M]p(z,\mu), \\
V_i &= \beta \mathrm{E}[V^0(\epsilon_S', \epsilon_I', \psi(1-\delta)k/\gamma; z', \mu')], \\
AC &= \xi\omega(z,\mu)p(z,\mu), \\
V_a &= -ip(z,\mu) + \beta \mathrm{E}[V^0(\epsilon_S', \epsilon_I', k'; z', \mu')], \\
\mu &= \text{distribution of } (\epsilon_S, \epsilon_I, k).
\end{aligned}$$

Households

- A continuum of identical households with access to a complete set of state-contingent claims
- Felicity function:

$$U(C, N^h) = \log C - AN^h$$

- The intertemporal price:

$$p(z, \mu) \equiv U_C(C, N^h) = 1/C(z, \mu).$$

- The intratemporal price:

$$\omega(z, \mu) \equiv -\frac{U_N(C, N^h)}{p(z, \mu)} = \frac{A}{p(z, \mu)}.$$

Recursive Equilibrium

A recursive competitive equilibrium is a set of functions

$$\omega, p, V^1, N, K', C, N^h, \Gamma$$

such that

1. *Production unit optimality*: Taking ω, p and Γ as given, demand N and K'
2. *Household optimality*: Taking ω and p as given, the household optimally chooses consumption C and labor N^h
3. *Commodity market clearing*
4. *Labor market clearing*
5. *Model consistent dynamics*: $\mu' = \Gamma(z, \mu)$.

Equilibrium Computation

- μ: infinite dimensional
- We follow Krusell and Smith:
  - approximate μ by its first moment over capital
  - approximate $\mu' = \Gamma(z, \mu)$ by a log-linear rule
- To simplify computations: $\rho_S = \rho_I$, the unit then only cares about $\epsilon \equiv \epsilon_S \epsilon_I$.

5. Confronting the evidence

Most parameters: standard values suggested by micro studies

No such values available for the adjustment cost parameter $\bar{\xi}$ and the maintenance parameter χ

Some options:

- Maximum likelihood?
- Match certain moments
- Moments from the distribution of plant level investment?
  - how many micro units in the model correspond to one observed micro unit?
- Moments suitable to gauge the relative importance of PE and GE smoothing

Sources of Smoothing in Macroeconomics

$$\begin{tikzcd} & \text{Aggregate Shocks} \arrow[dl] \arrow[dd] \arrow[dr] & \\ \text{micro frictions} \arrow[dr] & & \text{price responses} \arrow[dl] \\ & \text{Macro Aggregates} & \end{tikzcd}$$

Sources of Smoothing: Lumpy Investment Models

1. Micro frictions $\equiv$ PE smoothing:
   - it isn't only the size of adjustment costs
   - aggregation is central
   - Caplin and Spulber (1987) as an extreme example
2. Price responses $\equiv$ GE smoothing:
   - quasi labor supply
   - supply of funds

Our Calibration

- There are many combinations of PE and GE smoothing that achieve the same degree of aggregate smoothing
- Use 3-digit sectoral data to calibrate the relative importance of PE and GE smoothing
  - mainly partial equilibrium effects at this level:
- Benchmark calibration:
  - Match: $\sigma_{\text{sect}}(I/K)$, $\sigma_{\text{agg}}(I/K)$, $\pm\log(\sigma_{95}/\sigma_5)$
  - Parameters: $\bar{\bar{\xi}}$, χ, σ_A
- Robustness check:
  - Match: $\sigma_{\text{sect}}(I/K)$, $\sigma_{\text{agg}}(I/K)$
  - Parameters: $\bar{\bar{\xi}}$, σ_A

Standard Choices

- Model period: quarter
- Standard choices: $\beta = 0.9942$, $\delta = 0.022$, $\rho_A = 0.95$,...
- $\nu = 0.64$ and $\theta = 0.18$:
  - labor share: 0.64
  - revenue-elasticity of capital: 0.50
- $\sigma_S = 0.0273$, $\rho_S = 0.8612$: standard Solow residual calculation on *annual* 3-digit manufacturing data, taking into account sector-specific trends and time-aggregation
- $\sigma_I = 0.0472 \Rightarrow$ total s.d. $= 0.10$
- Non-trivial choices: $\bar{\xi}$ and χ

Results: Economic Magnitude of Adjustment Costs

	Tot. adj. costs/ Agg. Output	Tot. adj. costs/ Agg. Invest.	Adj. costs/ Unit Output	Adj. costs/ Unit Wage Bill
quart.	0.35%	2.41%	9.53%	14.88%
annual	0.41%	2.84%	3.60%	5.62%

Smoothing and $\sigma(I/K)$: RBC

$$
\begin{array}{ccc}
 & \text{No frictions} & \\
\swarrow & & \searrow \\
\begin{array}{c}\text{only PE} \\ 0\%\end{array} & \downarrow & \begin{array}{c}\text{only GE} \\ 100\%\end{array} \\
\searrow & & \swarrow \\
 & \begin{array}{c}\text{PE and GE} \\ 100\%\end{array} &
\end{array}
$$

Smoothing and $\sigma(I/K)$: Khan and Thomas

$$\begin{array}{ccccc} & & \text{No frictions} & & \\ & \swarrow & & \searrow & \\ \begin{array}{c}\text{only PE}\\ 16.1\%\end{array} & & \downarrow & & \begin{array}{c}\text{only GE}\\ 100\%\end{array} \\ & \searrow & & \swarrow & \\ & & \begin{array}{c}\text{PE and GE}\\ 100\%\end{array} & & \end{array}$$

Smoothing and $\sigma(I/K)$: This Paper

No frictions

$\swarrow$ $\searrow$

only PE $\downarrow$ only GE

81.0% 84.6%

$\searrow$ $\swarrow$

PE and GE

100%

Why the Difference?

We choose to match sectoral investment volatility:

	3-dig. Agg. Ratio
Data	*1.66*
This paper:	1.66
Frictionless/Khan-Thomas (2008):	18 - 44

We choose to match IRF volatility:

	$\log(\sigma_{95}/\sigma_5)$
Data	*0.30*
This paper:	0.29
Frictionless/Khan-Thomas (2008):	0.05

6. Aggregate Investment Dynamics

- Explain why our DSGE model with lumpy adjustment generates a procyclical IRF
- Is it variations in PE– or GE–smoothing?
- Is it related to the intensive or extensive margin?
- Relation to the "basic mechanism"

Responsiveness Index

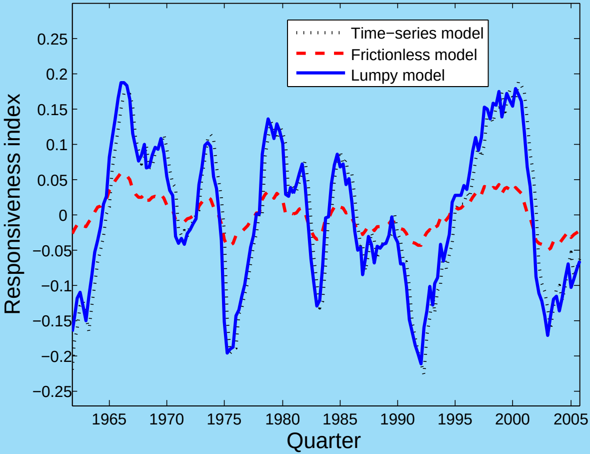
Define:

$$\mathcal{I}^{+}(\mu_t, \log z_t) \equiv \left[\frac{I}{K}(\mu_t, \log z_t + \sigma_A) - \frac{I}{K}(\mu_t, \log z_t)\right] / \sigma_A,$$
$$\mathcal{I}^{-}(\mu_t, \log z_t) \equiv \left[\frac{I}{K}(\mu_t, \log z_t - \sigma_A) - \frac{I}{K}(\mu_t, \log z_t)\right] / (-\sigma_A)$$

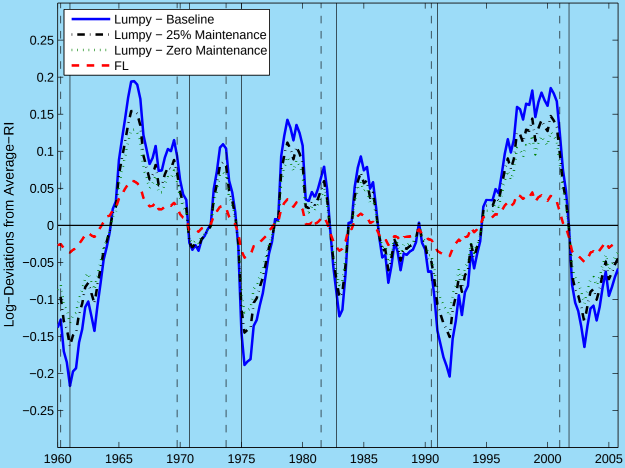
Responsiveness Index at time t defined as:

$$\mathrm{RI}_t \equiv 0.5\left[\mathcal{I}^{+}(\mu_t, \log z_t) + \mathcal{I}^{-}(\mu_t, \log z_t)\right].$$

IRF upon impact from model (1960–2005)



Robustness check – Second calibration



Why strongly procyclical?

- A decline in the strength of PE-smoothing explains the rise in the index during the boom phase
  - the responsiveness index fluctuates much less in the frictionless economy
  - frictionless economy only has GE-smoothing
  - hence: contribution of GE smoothing to fluctuations in responsiveness index of lumpy economy is small
- As the boom proceeds, the economy comes "closer" to the Caplin-Spulber limit

Mandated Investment

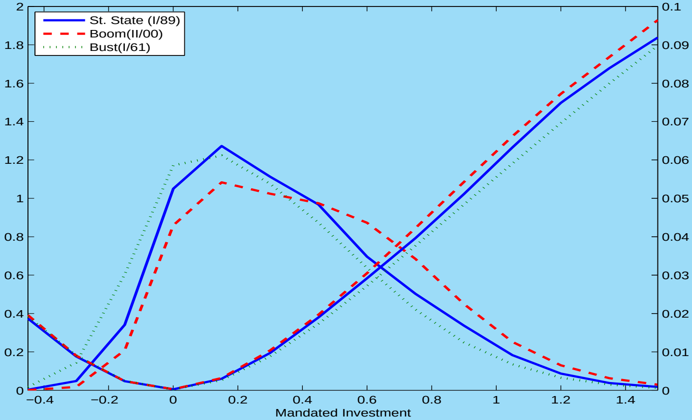
- We have:

$$k' = \begin{cases} k^*(\epsilon; z, \bar{k}), & \text{if } \xi \leq \xi^T(\epsilon, k; z, \bar{k}), \\ (1-\delta+\chi\delta)k, & \textit{otherwise}. \end{cases}$$

- We define mandated investment for a unit with current state $(\epsilon, z, \bar{k})$ and current capital k as:

$$x(\epsilon; z, \bar{k}) \equiv \log k^*(\epsilon; z, \bar{k}) - \log[1-\delta+\chi\delta]k.$$

Mandated Investment Cross-Section and Hazard

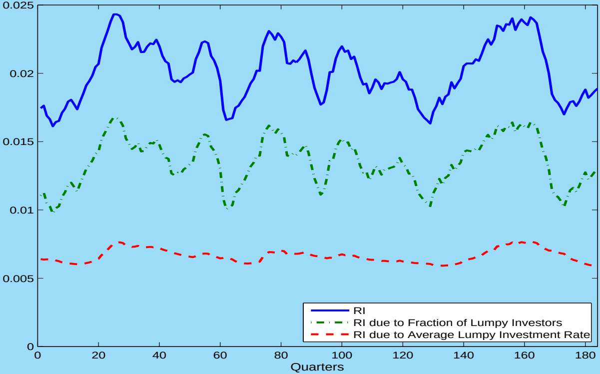


Why strongly procyclical?

During booms:

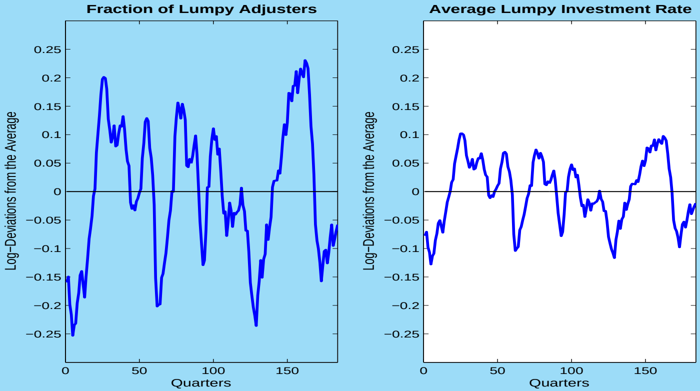
- the fraction of units with mandated investment close to zero decreases
- the fraction of units with mandated investment above 40% increases
- the fraction of units with negative mandated investment decreases
- the x-section moves intro regions where the probability of adjusting is higher and steeper
  - this effect is not present in a frictionless (or Calvo) model

RI: Intensive and Extensive Margins



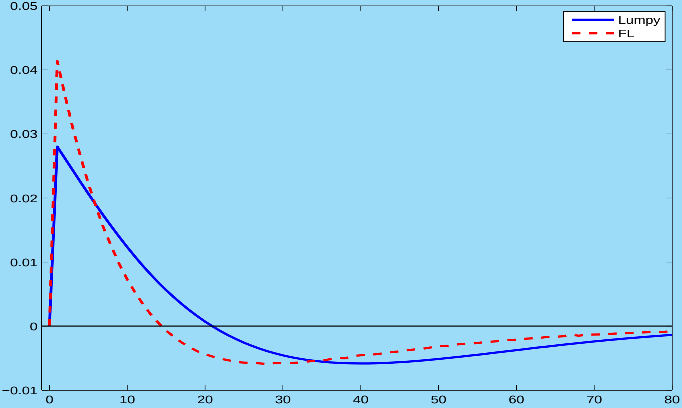
Fluctuations in responsiveness index driven mainly by variations in the fraction of units adjusting (extensive margin)

I/K: Intensive and Extensive Margins



Doms and Dunne (1998): it's the fraction of units undergoing major investment episodes

Understanding the Bust



- More capital accumulation in the lumpy economy
- Large fraction in region where units are unresponsive to shocks

7. Conclusion

- Time-series evidence suggests time-varying IRFs
- Lumpy adjustment DSGE models with mainly GE-smoothing forces cannot deliver history dependent IRFs
- Lumpy adjustment DSGE models where both PE and GE-smoothing are relevant deliver can