R&D, innovation, and productivity

Bronwyn H. Hall
University of California at Berkeley
NBER, IFS London, NIESR London, and Max Planck Institute Munich

R&D, innovation and productivity

- Many researchers have looked at the links among these 3 using data from the Community Innovation Survey and other similar surveys
- This presentation
  - Reviews what we know
  - Provides a framework for interpreting results
  - Draws some conclusions about how we might improve the data/analysis
  - Analysis reviews micro (individual firm-level, partial equilibrium) results only

Innovation and productivity

- What are the mechanisms connecting innovation and productivity?
  - Improvements within existing firms
    - Creation of new goods & services, leading to increased demand for firm's products
    - Process and organizational innovation leading to efficiency gains in production
  - Entry of more efficient firms
  - Entry of firms on technology frontier
  - Exit of less efficient firms

What do we know?

- A great deal about
  - the contribution of R&D and innovation to firm-level productivity as conventionally measured
- Something about
  - The contribution of entry of more efficient and exit of less efficient firms to aggregate productivity growth
  - The contribution of R&D to quality improvement and therefore productivity growth (via lower prices)
- Much less about
  - Contribution of R&D and innovation to welfare and to poorly measured but important outputs (health, environmental quality, etc)
  - Aggregate growth implications in detail

R&D vs innovation

- Not all innovative firms do formal R&D
- R&D-doing firms do not innovate every year (or even every 3 years)

Italian firms 1995-2006		
	Non-innovator	Innovator
Does not do R&D	30.9%	34.8%
Does R&D	6.2%	34.3%

- Especially true in the service sector:
  - Many innovations are not technological, such as new ways of organizing information flow, new designs, etc.
  - Many innovations rely on purchased technology, such as adoption of computer-aided processes, CRM software, etc.

R&D vs innovation spending

- UK firms on the CIS 1998-2006 – average breakdown of spending on innovative activities.
- Service sector firms spend more on new equipment and marketing and less on R&D.

	Manufacturing	Services & other
Acquisition of machinery & computer hardware/software	43.2%	47.0%
Internal R&D spending	25.1%	12.0%
Marketing expense	10.6%	16.5%
Training expense	5.4%	13.4%
Design expense	8.8%	4.2%
External R&D spending	4.2%	3.2%
Acquisition of external knowledge	2.6%	3.7%
Share with nonzero spending	71.1%	54.7%

The shares shown are for firms that have some form of innovation spending reported.

Measuring innovation

- Large literature using R&D flows or stocks as proxies for innovation input
    - Hall, Mairesse, Mohnen 2010 survey, *inter alia*
- Smaller literature using patents as a proxy for intermediate innovation output
- Both measures have well-known weaknesses, especially outside the manufacturing sector.
    - Most surveys of the service sector find many innovating firms, fewer R&D-doers
- Now we have more direct measures – do they help?

Innovation surveys contain…..

- Data on innovation:
  - Product or process new to firm/market (yes/no)
  - Share of sales during past 3 years from new products
  - More recent surveys have expenditures on various kinds of innovation investments
- Data on productivity and employment:
  - Usually sales per worker (labor productivity)
  - Sometimes TFP (adjusted for changes in capital)
  - Issues arising from deflation and level of aggregation
    - of goods, and of enterprises

More information in Mairesse and Mohnen (2010)

Interpretive framework

- Innovation-productivity regressions use revenue productivity data
  - Include coarse sectoral dummies
  - Relative within-sector price changes not accounted for
  - Quality change not generally accounted for
- In the case of innovative activity, omitting price change at the firm level can be helpful, as it allows estimation of the contribution of innovation to demand as well as efficiency
- Analysis of the implications of distinguishing productivity from revenue productivity
  - Based loosely on Griliches and Mairesse 1984

Productivity-innovation model

- Innovation will affect both the price the firm can charge and the quantity it produces from a given set of inputs
- Output measure -- revenue (sales) -- incorporates the joint response of price*quantity to product and process innovation
- Assume the following:
  - Imperfect competition (nonzero markup; downward sloping demand with constant elasticity)
  - Process innovation reduces cost (same inputs produce more)
  - Product innovation shifts demand curve out (higher willingness to pay for the same good, or higher quality good for the same price)

Algebra for this analysis given in backup slides

Product vs process

- Can one distinguish between innovative activity directed toward
  - new/improved products (increased demand) vs.
  - new/improved processes (increased efficiency)?
- Work by Petrin and Warzynski (2011) provides some evidence that the product/process distinction is meaningful
  - Danish micro data on wood products and iron & steel
  - R&D at the product/process level within firm.
  - Allows estimation of the contribution of R&D to demand (quality improvement) and technical efficiency separately
  - Finds product R&D more related to quality improvement and process R&D more related to technical efficiency
  - Work in progress

Conclusions

- Product innovation unambiguously increases *revenue productivity* and *labor demand*
- Process innovation will increase *revenue productivity* and *labor demand* only if demand is elastic; even in this case impact is dampened unless there is perfect competition (price taking)
- Allocation of the impact of innovation between price and quantity will depend on the type of price deflator used
  - the closer the deflator is to a true quality-adjusted price, the higher the *measured* innovation contribution to quantity rather than price (with a corresponding *negative* effect on price).
  - However, estimates of the innovation impact on firm *revenue* are not affected

What do the data say about this relationship?

Results from a large collection of papers that used the CDM model for estimation (Crepon Duguet Mairesse 1998):

- Innovation survey data reveals that some non-R&D firms innovate and some R&D firms do not innovate during the relevant period
- Data is usually cross-sectional, so possible simultaneity between R&D, innovation, and productivity (productivity sometimes measured a year later)
- Sequential model: R&D→innovation→productivity

The CDM model

1. The determinants of R&D choice: whether to do it and how much to do (generalized Tobit)
2. Innovation production function with innovation variables as functions of predicted R&D intensity (regression or probits)
3. Production function including the predicted innovation outcomes to measure their contribution to the firm's productivity.

Effectively a triangular simultaneous equations model, but nonlinear. (bootstrap s.e.s if sequentially estimated)

CDM model applied to CIS data

- Estimated for 20+ countries
- Confirms high rates of return to R&D found in earlier studies
- Like patents, innovation output statistics are much more variable ("noisier") than R&D,
  - R&D tends to predict productivity better, when available
- Next few slides - results summary
  - regressions of individual firm TFP on innovation
- Sources: Hall (2011), *Nordic Economic Policy Review* and Hall and Mohnen (2013), *Eurasian Business Review*

Productivity-innovation relationship in TFP levels

Sample	*Time period*	*Elasticity with respect to innov sales share*	*Process innovation dummy*
Chilean mfg sector	1995-1998	0.18 (0.11)*	
Chinese R&D-doing mfg sector	1995-1999	0.035 (0.002)***	
Dutch mfg sector	1994-1996	0.13 (0.03)***	-1.3 (0.5)***
Finnish mfg sector	1994-1996	0.09 (0.06)	-0.03 (0.06)
French mfg sector	1986-1990	0.07 (0.02)***	
German K-intensive mfg sector	1998-2000	0.27 (0.10)***	-0.14 (0.07)**
Norwegian mfg sector	1995-1997	0.26 (0.06)***	0.01 (0.04)
Swedish K-intensive mfg sector	1998-2000	0.29 (0.08)***	-0.03 (0.12)
Swedish mfg sector	1994-1996	0.15 (0.04)***	-0.15 (0.04)***
Swedish mfg sector	1996-1998	0.12 (0.04)***	-0.07 (0.03)***
Swedish service sector	1996-1998	0.09 (0.05)*	-0.07 (0.05)
Innovative sales share and process innovation included separately in the production function:			
French Hi-tech mfg	1998-2000	0.23 (0.15)*	0.06 (0.02)***
French Low-tech mfg	1998-2000	0.05 (0.02)***	0.10 (0.04)***
Irish firms	2004-2008	0.11 (0.02)***	0.33 (0.08)***

TFP levels on innov sales share

- Robustly positive, supports the view that product innovation shifts the firm's demand curve out and increases revenue
  - Elasticities range from 0.04 to 0.29 with a typical standard error of 0.03
  - R&D-intensive and hi-tech firms have higher elasticities (consistent with equalized rates of return across sectors)
- Coefficient of process innovation dummy usually insignificant or negative, suggesting either inelastic demand and/or substantial measurement error in the innovation variables

Productivity-innovation using dummies

Sample	*Time period*	*Product innovation dummy*	*Process innovation dummy*
Argentinian mfg sector	1998-2000	-0.22 (0.15)	
Brazilian mfg sector	1998-2000	0.22 (0.04***	
Estonian mfg sector	1998-2000	0.17 (0.08)**	-0.03 (0.09)
Estonian mfg sector	2002-2004	0.03 (0.04)	0.18 (0.05)***
French mfg sector	1998-2000	0.08 (0.03)**	
French mfg sector	1998-2000	0.06 (0.02)***	0.07 (0.03)**
French mfg sector	1998-2000	0.05 (0.09)	0.41 (0.12)***
French mfg sector	2002-2004	-0.08 (0.13)	0.45 (0.16)***
French service sector	2002-2004	0.27 (0.52)	0.27 (0.45)
German mfg sector	1998-2000	-0.05 (0.03)	0.02 (0.05)
Italian mfg sector	1995-2003	0.69 (0.15)***	-0.43 (0.13)***
Italian mfg sector SMEs	1995-2003	0.60 (0.09)***	0.19 (0.27)
Mexican mfg sector	1998-2000	0.31 (0.09)**	
Spanish mfg sector	2002-2004	0.16 (0.05)***	
Spanish mfg sector	1998-2000	0.18 (0.03)***	-0.04 (0.04)
Swiss mfg sector	1998-2000	0.06 (0.02)***	
UK mfg sector	1998-2000	0.06 (0.02)***	0.03 (0.04)
Innovative sales share and process innovation included separately in the production function:			
Irish firms	2004-2008	0.45 (0.08)***	0.33 (0.08)***

Productivity-innovation using dummies

Sample	*Time period*	*Product innovation dummy*	*Process innovation dummy*
German mfg sector	2006-2008	0.04 (0.02)*	
German mfg sector	2006-2008		0.09 (0.05)**
German service sector	2006-2008	0.21 (0.07)***	
German service sector	2006-2008		0.16 (0.06)***
Irish mfg sector	2006-2008	0.18 (0.22)	
Irish mfg sector	2006-2008		0.24 (0.24)
Irish service sector	2006-2008	0.51 (0.30)*	
Irish service sector	2006-2008		0.19 (0.28)
UK mfg sector	2006-2008	0.05 (0.02)***	
UK mfg sector	2006-2008		0.07 (0.02)***
UK service sector	2006-2008	0.07 (0.03)**	
UK service sector	2006-2008		0.04 (0.02)*

Source: Peters et al. 2014

TFP level results with dummies

- Product dummy supports innovation sales share result, although much noisier.
- There is substantial correlation between product and process innovation, especially when they are instrumented by R&D and other firm characteristics.
  - Without instruments, innovation dummies frequently do not enter productivity equation at all.

NB: Correlated measurement error can lead to bias in both coefficients (upward for the better measured one and downward for the other) – see Hall (2004) http://bronwynhall.com/papers/BHH04_measerr.pdf

Employment impacts

- Harrison et al (IJIO 2014) and Hall, Lotti, Mairesse (ICC 2008) - decompose employment change as a function of process and product innovation, using coefficients from a regression of employment growth on innovative sales growth and process innovation:

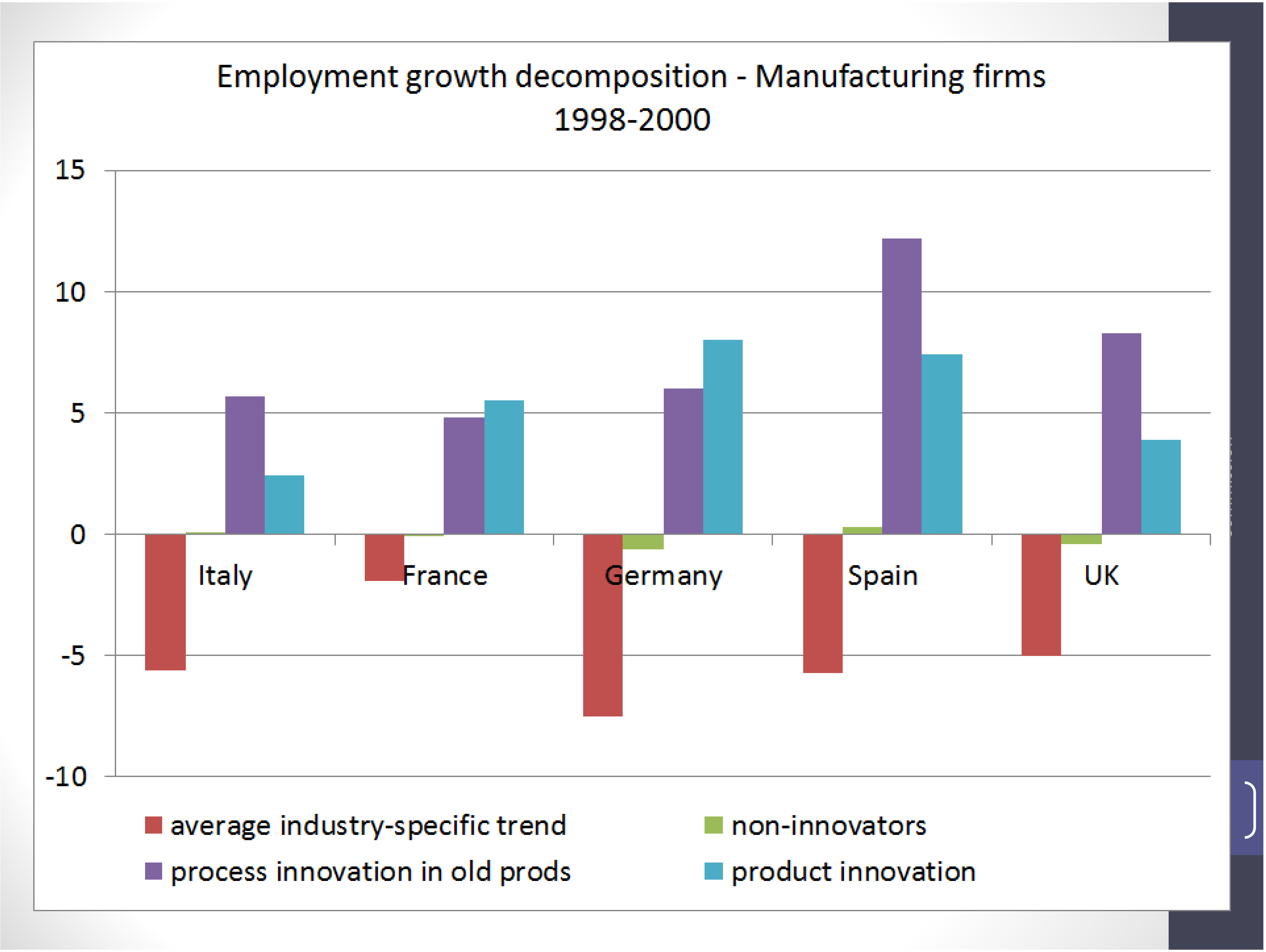
  Growth = industry productivity trend in old products

  + growth due to process innovation in old products

  + growth due to output growth of old products

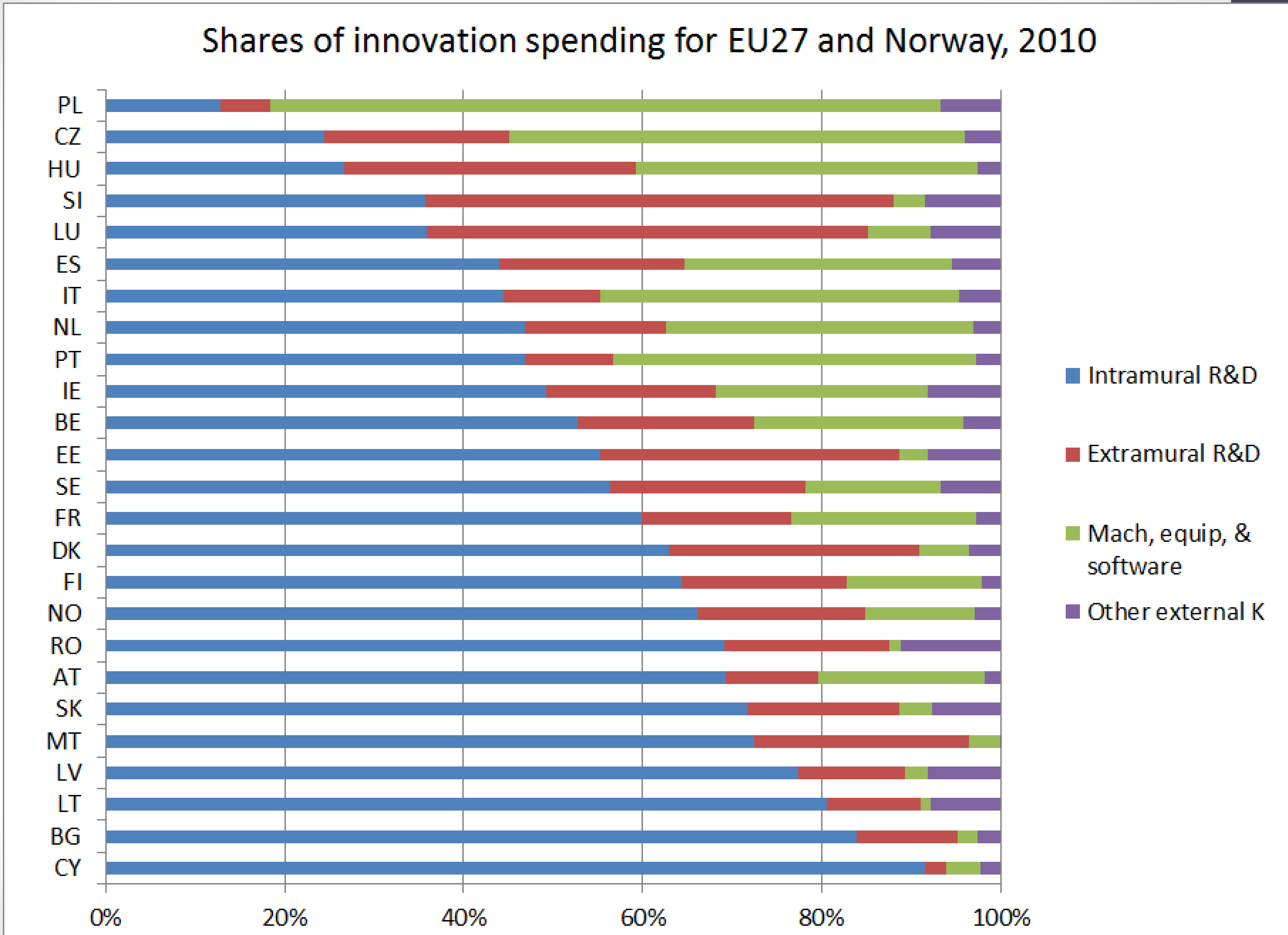
  + growth due to product innovation (net of substitution away from old products)

- A reinterpretation of the labor productivity equation to focus on employment


Employment growth decomposition - Manufacturing firms
1998-2000
15
10
5
0
-5
-10
Italy
France
Germany
Spain
UK
average industry-specific trend
non-innovators
process innovation in old prods
product innovation

Summary

- Elasticity wrt innovative sales centers on (0.09, 0.13)
  - higher for high tech and knowledge-intensive firms
  - Lower on average for low tech and developing countries, but also more variable
- With product innovation included, process innovation often negative or zero
- Without product innovation, process innovation positive for productivity
- When not instrumented, little impact of innovation variables in production function (unlike R&D)
  - See Mairesse & Mohnen (2005), Hall et al. (2012)
- Both process and product innovation are positive on average for firm employment growth in manufacturing,
  - at least during the late 1990s in Europe
- What if we had spending on innovation (rather than just R&D, a component of innovation spending)?


Shares of innovation spending for EU27 and Norway, 2010
PL
CZ
HU
SI
LU
ES
IT
NL
PT
IE
BE
EE
SE
FR
DK
FI
NO
RO
AT
SK
MT
LV
LT
BG
CY
0%
20%
40%
60%
80%
100%
Intramural R&D
Extramural R&D
Mach, equip, & software
Other external K

UK evidence

- Definition of IS: internal & external R&D; new equip & software; design expense; training; acq of patents & knowhow; marketing – all associated with intro of new products or processes
- Out of 10,500 firm obs 2001-2006
  - 6500 have some form of innovation spending (IS)
  - 3400 have internal R&D
  - R&D firms: median IS is 5 times median R&D
- Compared to R&D:
  - IS more strongly associated with info from suppliers and innovation to meet environmental or H&S stds; less strongly with exports, collaboration, and info from customers (that is, more process than product)
  - IS is a better predictor of innovation probability
  - Doubling IS has the same impact on TFP as doubling R&D – increase of 0.05

Discussion

- R&D spending remains a better predictor of productivity improvement at the firm level
- Innovation dummies may be too noisy a measure to be very useful.
  - Share of sales due to new products is more informative.
  - What measure would be useful (and reportable) for process innovation?
- Further exploration with innovation investment (instead of R&D) is warranted

Thank you for listening

Backup Slides

Technical detail for production function with innovation

Conventional productivity equation

$$r_{it} = a_{it} + \alpha c_{it} + \beta l_{it} \qquad i = entity, t = time$$

r = log value added (sometimes just output)

c = log tangible capital

l = log labor input

a_{it} = TFP (total factor productivity)

Coefficients *α, β* measured as shares (growth accounting) or by regression (econometric)

R&D or innovation often added to this equation to measure productivity impacts

Revenue productivity

- Firm (enterprise) level: measure sales, value added, or revenue, the product of (relative) price and quantity, not quantity alone
- Equation in logarithms, so left hand side is sum of price and quantity

$$r_{it} \equiv \log R_{it} = \log P_{it} + \log Q_{it}$$

- Coefficients measure the sum of price and quantity impact from changes in capital, labor, and R&D or innovation

Revenue productivity

If firms have market power and idiosyncratic prices, we observe real revenue *r*, not output *q*:

$r = p+q$ (all in logs)

Add a CES demand equation: $q_{it} \sim \eta p_{it}$, $\eta<0$

Then the revenue productivity relationship is

$$r_{it} = \text{const} + \left(\frac{\eta+1}{\eta}\right)(a_{it} + \alpha c_{it} + \beta l_{it}) \sim \left(\frac{\eta+1}{\eta}\right) q_{it}$$

If imperfect competition ($\eta>-\infty$), revenue impact is dampened relative to output; if demand is inelastic ($0>\eta>-1$), revenue falls with increased output

Adding innovation

Add two terms involving knowledge stock:

process: γk_{it} in the production function, $\gamma>0$

product: φk_{it} in the demand function, $\varphi>0$

This yields the following revenue function:

$$r_{it} = C + \left(\frac{\eta+1}{\eta}\right)\left(a_{it} + \alpha c_{it} + \beta l_{it}\right) + \left(\frac{\gamma(\eta+1)-\varphi}{\eta}\right)k_{it}$$

Product improvement from k $(-\varphi/\eta)$ is always positive for revenue

Process improvement from k $(\gamma(\eta+1)/\eta)$ could be small or even negative

Implication for prices

Recall that $q_{it} = \eta p_{it} + \varphi k_{it}$

Then

$$p_{it} = \left(\frac{1}{\eta}\right)\left(a_{it} + \alpha c_{it} + \beta l_{it}\right) + \left(\frac{\gamma - \varphi}{\eta}\right)k_{it}$$

If demand elasticity is constant, price falls with innovation if γ-$\varphi > 0$ (recall $\eta<0$)

That is, if efficiency enhancement effect outweighs product improvement effect

Impact of innovation on price greater the more inelastic is demand, *c.p.*

Implication for employment

- Similar to that for output
- Short run profit maximization given ordinary and innovation capital yields labor demand as a function of capitals:

$$l_{it} \sim \left(\frac{\eta + 1}{\eta(1-\beta) - \beta} \right) (a_{it} + \alpha c_{it}) + \left(\frac{\gamma(\eta + 1) - \varphi}{\eta(1-\beta) - \beta} \right) k_{it}$$

- Denominator is always negative =>
  - Process effect of *k* is negative for labor demand if demand is inelastic
  - Product effect of *k* always positive for labor demand

Econometrics (1)

Only some firms report R&D; use standard selection model:

Selection eq

$$RDI_i = \begin{cases} 1 & if \quad RDI_i = w_i\alpha + \varepsilon_i > \overline{c} \\ 0 & if \quad RDI_i = w_i\alpha + \varepsilon_i \le \overline{c} \end{cases}$$

Conditional on doing R&D, we observe the level:

$$RI_i = \begin{cases} RD_i^* = z_i\beta + e_i & if \quad RDI_i = 1 \\ 0 & if \quad RDI_i = 0 \end{cases}$$

Assume joint normality => generalized tobit or Heckman selection model for estimation.

Econometrics (2)

Output of the KPF are various binary innovation indicators or the share of innovative sales. For example,

$$DI_i \sim \phi\left(RD_i^* \gamma + X_i \delta + u_i\right)$$

DI = Dummy for innovation (process, product, organizational)

Φ (.) = normal density

Why include the latent R&D variable *RD**?

1. Account for informal R&D effort that is often not reported
2. Instrument for errors in variables and simultaneity

Estimation is via multivariate probit

Econometrics (3)

Production function:

$$y_i = \pi_1 k_i + \sum_j \pi_{2j} DI_{ij} + Z_i \varphi + \nu_i$$

y = log sales per employee

k = log capital stock per employee

DI are predicted probabilities of innovation from second step or predicted share of innovative sales (with logit transform)

Z includes size, age, industry, region, year, wave

Estimated by OLS

Aggregation

- How does individual firm relationship aggregate up to macro-economy?
  - productivity gains in existing firms
  - exit and entry
- Aghion et al (2009); Gorodnichenko et al (2010)
  - Competition and entry encourages innovation unless the sector is very far behind
- Djankov (2010) survey – cross country
  - stronger entry regulation and/or higher entry costs associated with fewer new firms, greater existing firm size and growth, lower TFP, lower investment, and higher profits

Entry and exit

- Olley & Pakes, Haltiwanger & co-authors have developed decompositions that are useful
- Foster, Haltiwanger, and Syverson (2008) – US data
  - Distinguish between revenue and quantity, and include exit & entry
  - Revenue productivity understates contribution of entrants to real productivity growth because entrants generally have lower prices
  - Demand variation is a more important determinant of firm survival than efficiency in production (consistent with productivity impacts)

Future work?

- Full set of links between innovation, competition, exit/entry, and productivity growth not yet explored
- Bartelsman et al. (2010): Size-productivity more highly correlated within industry if regulation is "efficient"
  - Evidence on Eastern European convergence
  - Useful approach to the evaluation of regulatory effects without strong assumptions
- Similar analysis could assess the economy-wide innovation impacts