A new approach to estimating private returns to R&D

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Workhorse model

Workhorse model of output (for a firm i in year t) that uses R&D as an input factor:

$$\ln Y = \beta \ln r + \gamma \ln K + \varepsilon \ln L + \rho \ln M$$

- Output (Y) depends on a measure of R&D stock or -services (r) in addition to the standard inputs tangible capital (K), labour (L), and intermediates (M).
- Strong implications for estimating *returns* to R&D:
  - constant elasticity with respect to R&D ($= \beta$)
  - marginal returns to R&D is:

$$Y'_F = \beta Y / r$$

which tends to infinity at the extensive margin ($r = 0$) and is not even defined for firm with no R&D ($r = 0$).

Our refinements

- We assume that the production function has output elasticity of β in a *translation* of F:

$$r(\lambda) = \lambda + F$$

  for some value of $\lambda > 0$ to be optimally chosen.
- Allow β to be firm-specific (β_i) to accommodate the huge observed heterogeneity in R&D intensity across firms.
- Quality adjustment of labour: production function has output elasticity of degree ε in an *aggregate* $g(L)$ of $L = (L^{(1)}, L^{(2)}, L^{(3)})$ – a vector of man-years from three skill classes based on educational attainments.

Measuring R&D

In the tradition of Hall and Mairesse (1995), F is the R&D capital stock generated by accumulating R&D spending according to the perpetual inventory method (PIM):

$$F_t = (1 - \delta)F_{t-1} + I_{t-1},$$

where

- I is (real) R&D investment
- δ is the depreciation rate of the R&D capital stock, usually assumed to be 0.15

Double counting

A researcher's wage costs, wL, may be intramural R&D ($int = wL$) for the R&D performing firm. Double counting would occur if L is also counted as labour inputs (see Schankerman, 1981).

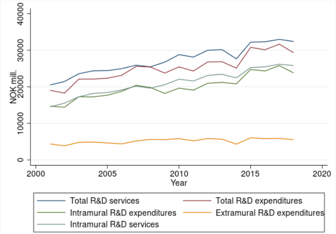
- We will address this issue by deriving a value added function that depends, not on labour (L), but on the wage rate (w).

Asymmetric treatment of intramural and extramural R&D

A double-counting problem often overlooked is related to extramural R&D (x), where, for example, $int = wL$ for the R&D performing firm and $x = wL$ for the financing firm.

The Frascati Manual recommends:

- capitalizing R&D performed but not R&D financed
- treat extramural R&D (x) as intermediate input (M)



Economic behavior

- Cost minimization w.r.t. L and M for *pre-determined* R&D capital stock, F, and tangible capital stock, K
- Firms choose the output price (P) that maximizes operating profits under assumption of monopolistic competition (some market power), with demand given by:

$$Y = \Phi P^{-e}$$

Value added function

Structurally derived expression for value added (V=profits + labour earnings):

$$\ln V_{it} = -\widetilde{\varepsilon} \ln c_{it} + \widetilde{\beta}_i \ln r_{it}(\lambda) + \widetilde{\gamma} \ln K_{it} - \widetilde{\rho} \ln q_{Mt} + \widetilde{a}_{it}$$

where $\widetilde{\varepsilon} = \varepsilon\vartheta$, $\widetilde{\beta}_i = \beta_i\vartheta$, $r_{it}(\lambda) = \lambda + F_{it}$, $\widetilde{\gamma} = \gamma\vartheta$, $\widetilde{\rho} = \rho\vartheta$, and $\widetilde{a}_{it} = \vartheta(\ln A_{it} + \ln \Phi_{it}/(e-1)) + \widetilde{\theta}$, with

$$\vartheta = \frac{(e-1)}{(\varepsilon + \rho + e - e(\varepsilon + \rho))} \in (0, (1 - \varepsilon - \rho)^{-1}).$$

Log-wage

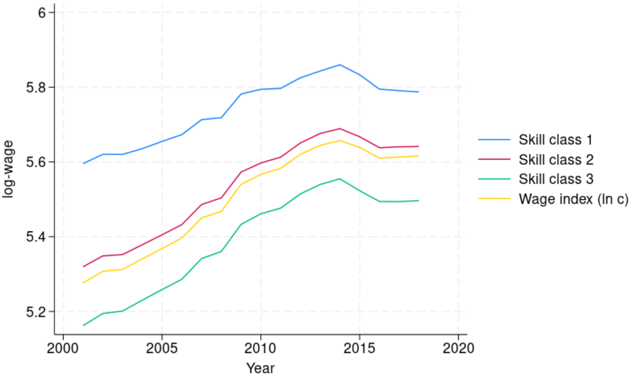


Figure: Average log-wage by skill class and average *Sato-Vartia* log-wage index ($\ln c_{it}$)

Returns to R&D

- We define

$$R_{it} = \frac{\partial V_{it}}{\partial F_{it}} = \frac{\widetilde{\beta}_i V_{it}}{F_{it} + \lambda}$$

as our proposed value added-based measure of private returns to R&D investment

- In the tradition of Hall et al. (2010), it is often assumed that R_{it} varies randomly about a common mean, R, where R is the constant marginal *cost* of R&D (“CMC-model”).

To apply this assumption in our context, assuming F and K to be pre-determined, we state the existence of a steady state as follows:

$$E(R_{it}|F_{it}, K_{it}) = \frac{\widetilde{\beta}_i E(V_{it}|F_{it}, K_{it})}{F_{it} + \lambda} = R$$

By “double expectation”:

$$\widetilde{\beta}_i = R\psi_i(\lambda)$$

where

$$\psi_i(\lambda) = \frac{E(F_{it}|F_{it} > 0) + \lambda}{E(V_{it}|F_{it} > 0)}$$

Equilibrium R&D intensity

- The function $\psi_i(\lambda)$ represents a firm-specific equilibrium ratio between V_{it} and F_{it} (with $F_{it} > 0$).
- The empirical counterpart is:

$$\overline{\psi}_i(\lambda) = \frac{\sum_{t=1}^{T} 1_{F_{it}>0}(F_{it} + \lambda)}{\sum_{t=1}^{T} 1_{F_{it}>0} V_{it}}$$

  which is useful for eliminating the nuisance parameter β_i
- In the literature, the usual assumption is that $\beta_i = \beta$ (no heterogeneity in the elasticity of Y with respect to F).
- We will refer to this special case as the restricted CMC model (R-CMC), which can be stated as:

$$\widetilde{\beta} = R\psi(\lambda)$$

Adjustment costs

- In the presence of adjustment costs, firms with a short R&D history are likely to be far from their equilibrium R&D intensity (and therefore $\overline{\psi}_i(\lambda)$ severly biased as an estimator of $\psi_i(\lambda)$).
- A sparse literature on the implications of adjustment costs of R&D investment suggests higher rates of return for firms that invest relatively more in R&D (see Resutek 2022).
- Brasch et al. (2020) show that start-up firms have much lower revenue labour productivity, V_{it}/L_{it}, than incumbent firms, indicating that “R&D productivity”, V_{it}/F_{it}, may be lower for “R&D-beginners” than “R&D-incumbents” .

Operationalizations

- We assume

$$\psi_i(\lambda) \simeq \overline{\psi}_i(\lambda)(1 + \tau_{begin})$$

for "R&D-beginners", implying weighted average return of:

$$\sum_{t=1}^{T} \omega_{it} R_{it} \simeq R(1 + \tau_{begin})$$

- A negative parameter τ_{begin} would capture low returns to R&D in firms with little R&D experience relative to "R&D-incumbents".
- Similarly we assume:

$$\psi_i(\lambda) \simeq \overline{\psi}_i(\lambda)(1 + \tau_{exper})$$

for "R&D-experienced" firms – i.e. firms with *some* R&D experience

Empirical model

The dependent variable in the empirical analysis is $\ln V_{it}$ and the stochastic specification of the structural equation is:

$$\ln V_{it} = -\widetilde{\varepsilon} \ln c_{it} + \widetilde{\gamma} \ln K_{it} + \widetilde{\beta}_i \ln r_{it}(\lambda) + a_i + \mu_t^* + \zeta_{it}$$

where a_i is a fixed firm effect, μ_t^* is the fixed time-effect, and ζ_{it} is a n AR(1) error term:

$$\zeta_{it} = \phi \zeta_{i,t-1} + e_{it}$$

GMM

We quasi-difference to eliminate the fixed firm effect and the AR(1) error term:

$$\begin{aligned}\Delta \ln V_{it} &= \phi \Delta \ln V_{i,t-1} - \widetilde{\varepsilon} \Delta \ln c_{it} + \phi \widetilde{\varepsilon} \Delta \ln c_{i,t-1} + \widetilde{\beta}_i \Delta \ln r_{it}(\lambda) \\ &- \phi \widetilde{\beta}_i \Delta \ln r_{i,t-1}(\lambda) + \widetilde{\gamma} \Delta \ln K_{it} - \phi \widetilde{\gamma} \Delta \ln K_{i,t-1} + \Delta \mu_t + \Delta e_{it}\end{aligned}$$

This equation constitutes the basis for GMM estimation.

Moment conditions

For given λ, the GMM-estimator uses the following moments (in the tradition of Arellano and Bond, 1991):

$$E(\ln V_{i,t-s}\Delta e_{it}) = 0$$
$$E(\ln c_{i,t-s+1}\Delta e_{it}) = 0$$
$$E(\ln r_{i,t-s+1}(\lambda)\Delta e_{it}) = 0$$
$$E(\ln K_{i,t-s+1}\Delta e_{it}) = 0$$

for $s \geq 2$. That is:

- We treat *all* the right-hand side variables as pre-determined endogenous variables.
- A testable identifying assumption is that Δe_{it} is an MA(1) noise term.
- Over-identifying restrictions can also be tested.

Optimal choice of translation parameter

To estimate or calibrate λ, we maximize the generalized R^2 model selection criterion proposed by Pesaran and Smith (1994) in the context of IV estimation

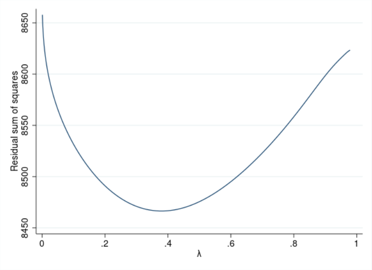


TABLE 1: **Estimates of the coefficients of the value added equation with symmetric treatment of intramural and extramural R&D ($I = int + x$). Robust standard errors (SE)**

Indep. variables in structural equation	Coeff.	GMM-estimates CMC Est.	GMM-estimates CMC SE	GMM-estimates R-CMC Est.	GMM-estimates R-CMC SE	FE-estimates R-CMC Est.	FE-estimates R-CMC SE
$\ln V_{i,t-1}$	ϕ	.306	.011***	.311	.021***		
$-\ln c_{it}$	$\widetilde{\varepsilon}$	.502	.164***	.509	.167***	.639	.110***
$\ln K_{it}$	$\widetilde{\gamma}$	.195	.016***	.207	.016***	.166	.006***
$\ln r_{it}(\lambda)$	$\widetilde{\beta}$			.045	.003***	.042	.002***
$\overline{\psi}_i(\lambda) \ln r_{it}(\lambda)^1$	R	.181	.049***				
$\overline{\psi}_i(\lambda) 1_{(T_i \leq 3)} \ln r_{it}(\lambda)^2$	τ_{begin}	-.180	.049***				
$\overline{\psi}_i(\lambda) 1_{(T_i \in [4,12])} \ln r_{it}(\lambda)$	τ_{exper}	-.029	.053				
σ_e^2		.11		.11		—	
σ_ζ^2		—		—		.41	
λ		.38		.38		.38	
Number of firm-years		40,344		40,344		40,344	
Number of firms		4,590		4,590		4,590	
R-squared $(R^2)^3$		.10		.10		.41	

Note: Windmeijer (2005) robust standard errors (SE); *,**,*** refer, respectively, to significant estimates at the 10, 5, and 1 percent level.

[1] $\overline{\psi}_i(\lambda)$ refers to the firm's average R&D intensity, as defined in Equation (15).

[2] T_i is the number of years with $F_{it} > 0$ in the years 2001-2018.

[3] R^2 refers to (the differenced) Equation (22) in the case of GMM and (the level) Equation (19) in the case of FE.

TABLE 3: **Distribution of estimated marginal gross returns to R&D (R_{it}) with symmetric treatment of intramural and extramural R&D ($I = int + x$). By subsample, conditional on $F_{it} > 0$**

Model	**All obs.** $F_{it} > 0$	**Subsample with** $F_{it} > 0$ **R&D-begin.**[1]	**R&D-exper.**[2]	**R&D-incumb.**[3]
CMC: heterogeneous elast.				
Weighted average[4)]	.173	.001	.146	.177
Median	.169	.001	.153	.190
Unweighted average	.270	.001	.276	.294
R-CMC: common elasticity				
Weighted average	.209	.628	.334	.191
Median	.422	.678	.520	.344
Unweighted average	6.47	8.56	6.17	6.45
Share of R&D in 2018 (share $\sum_i F_{i,2018}$)	1	.05	.17	.78
No. of firm-years with $F_{it} > 0$	30,331	2,370	15,507	27,822
No. of firms with $F_{it} > 0$	4,238	1,046	2,146	1,046

Note: Derived using the GMM estimates displayed in Table 1

[1] Firms that were R&D-active (i.e., with $F_{it} > 0$) for maximum 3 years in the period 2001-2018

[2] Firms that were R&D-active for between 4 and 12 years in the period 2001-2018

[3] Firms that were R&D-active for more than 12 years in the period 2001-2018

[4] Weighted by share of R&D (F_{it})

TABLE 5: **Distribution of estimated marginal gross returns to R&D (R_{it}) when only intramural R&D are treated as investments ($I = int$). By subsample, conditional on $F_{it} > 0$**

Model	**All obs.** $F_{it} > 0$	**Subsample with** $F_{it} > 0$ **R&D-begin.**[1]	**R&D-exper.**[2]	**R&D-incumb.**[3]
CMC: heterogeneous elast.				
Weighted average[4)]	.256	.001	.184	.268
Median	.238	.001	.153	.194
Unweighted average	.339	.002	.276	.287
R-CMC: common elasticity				
Weighted average	.241	.900	.334	.221
Median	.420	.655	.493	.357
Unweighted average	3.71	5.03	3.05	4.01
Share of R&D in 2018 (share $\sum_i F_{i,2018}$)	1	.05	.17	.78
No. of firm-years with $F_{it} > 0$	30,331	2,370	15,507	27,822
No. of firms with $F_{it} > 0$	4,238	1,046	2,146	1,046

Note: Derived using the GMM estimates displayed in Table 4.
[1] Firms that were R&D active (i.e., with $F_{it} > 0$) in maximum 3 years in 2001-2018
[2] R&D active firms between 4 and 12 years in 2001-2018
[3] R&D active firms for more than 12 years in 2001-2018
[4] Weighted by share of R&D (F_{it})

TABLE 6: **Distribution of marginal gross returns to R&D (R_{it}) estimated using Cobb-Douglas production function ($\lambda = 0$) and different definitions of R&D investment. By subsample, conditional on $F_{it} > 0$**

Model	All obs.	Subsample with $F_{it} > 0$		
	$F_{it} > 0$	R&D-begin.[1]	R&D-exper.[2]	R&D-incumb.[3]
Symmetric treatment of intramural and extramural R&D ($I = int + x$)				
CMC: heterogeneous elast.				
Weighted average[4)]	.138	-.241	.241	.150
Median	.116	-.270	.052	.161
Unweighted average	.172	-.373	.276	.248
R-CMC: common elasticity				
Weighted average	.637	1.23	1.33	.598
Median	1.21	1.48	1.54	1.06
Unweighted average	24.9	63.5	20.82	25.78
Only intramural R&D treated as investment ($I = int$)				
CMC: heterogeneous elast.				
Weighted average[4)]	.249	-.295	.241	.253
Median	.267	-.330	.270	.271
Unweighted average	.357	-.429	.357	.390
R-CMC: common elasticity				
Weighted average	.991	2.84	1.33	.939
Median	1.65	2.04	1.96	1.49
Unweighted average	16.05	19.09	13.07	17.59

Note: Returns estimates derived from models estimated using GMM on subsample of observations with $F_{it} > 0$. See Table 9 in Appendix C.

[1] Firms that were R&D-active (i.e., with $F_{it} > 0$) for maximum 3 years in the period 2001-2018

[2] Firms that were R&D-active for between 4 and 12 years in the period 2001-2018

[3] Firms that were R&D-active for more than 12 years in the period 2001-2018

Conclusion

- We have proposed an extended Cobb-Douglas production function, which allows for firms with zero R&D capital.
- We incorporated heterogeneity in labour quality.
- We have obtained robust (weighted) average *net* return estimates of 5-10 percent (gross return less $\delta = 0.15$).
- We have accommodated the huge observed heterogeneity in R&D intensities by allowing R&D elasticities to be firm-specific, which is key to obtain robust estimates of returns to R&D within a family of model variants