Learning and Forgetting: The Dynamics of Aircraft Production

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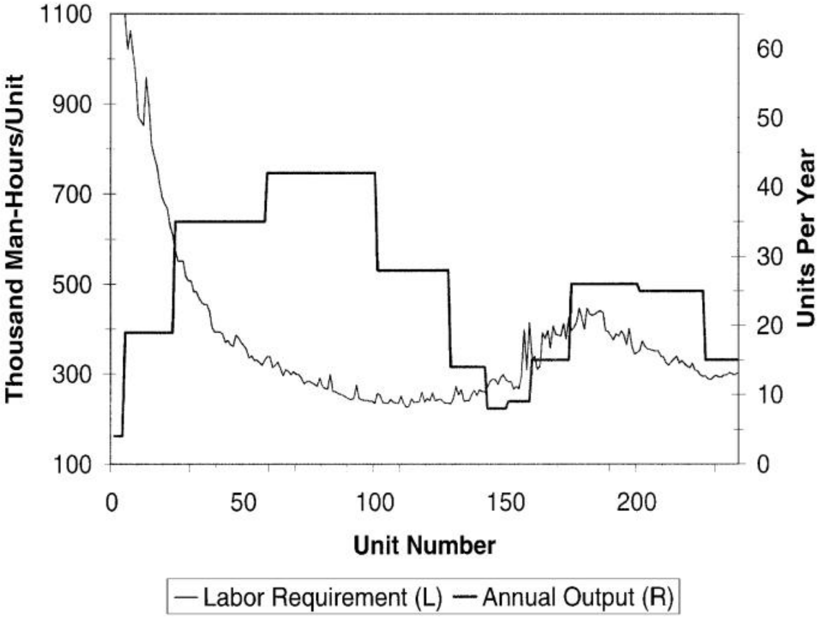
Overview

- Well-documented process of learning in organizations as they increase production over time.
- But do organizations also *forget* over time?
- Benkard looks at detailed data on aircraft production at Lockheed from 1970–1984, and estimates a variety of production functions to see which one fits best.
  - Also looks at imperfect spillovers across models.

Definition (Organizational Forgetting)

The hypothesis that the firm's production experience depreciates over time.

Data (Motivation)



Industry Overview

- Unlike military contracts, highly volatile demand/output for commercial planes.

- Reasonable amounts of competition; firms compete for customers by offering customizable options (in this case another model type).

- Labor heavily unionized, and seniority structure leads to very high turnover (extra scope for retraining and forgetting).

Model of Production

$$q = \min(G(L, E, \overline{K}, S, \varepsilon), H(M, E, \overline{K}, S, \nu)) \qquad \text{(Leontief)}$$

- E is experience (the main focus in the paper)
- S is line speed (endogenous)
- ε is a productivity shock to labor
- ν is a productivity shock to materials
- Will talk about $G(\cdot)$ and $H(\cdot)$ later

Recall that unit production is very low, so E changes meaningfully for each unit, and it's not crazy to think firms are adjusting variable inputs for each unit.

Experience

$$E_i = E_{i-1} + 1; \quad E_1 = 1 \qquad \text{(baseline)}$$

$$E_i = \delta E_{i-1} + q_{t-1} \qquad \text{(with forgetting)}$$

$$E_i = \begin{cases} E_{1,t} & : \quad i \in \{-1, -100, -200\} \\ E_{500,t} & : \quad i = -500 \end{cases} \qquad \text{(inc. spillovers)}$$

$$\begin{aligned} E_{1,t} &= \delta E_{1,t-1} + q_{1,t-1} + \lambda q_{500,t-1} \\ E_{500,t} &= \delta E_{500,t-1} + \lambda q_{1,t-1} \end{aligned}$$

- λ is the experience spillover parameter
- $\delta = 1$ and $\lambda = 1$ recovers the baseline case

Estimation

- Estimation via GMM; need instruments for line speed and experience
- Line speed should be correlated with current output; experience should be correlation with recent output
- Benkard uses current and lagged demand and cost shifters
- **Demand Shifters:** Various world GDP measures, oil price, time trend
- **Cost Shifters:** World aluminum price and U.S. manufacturing wage

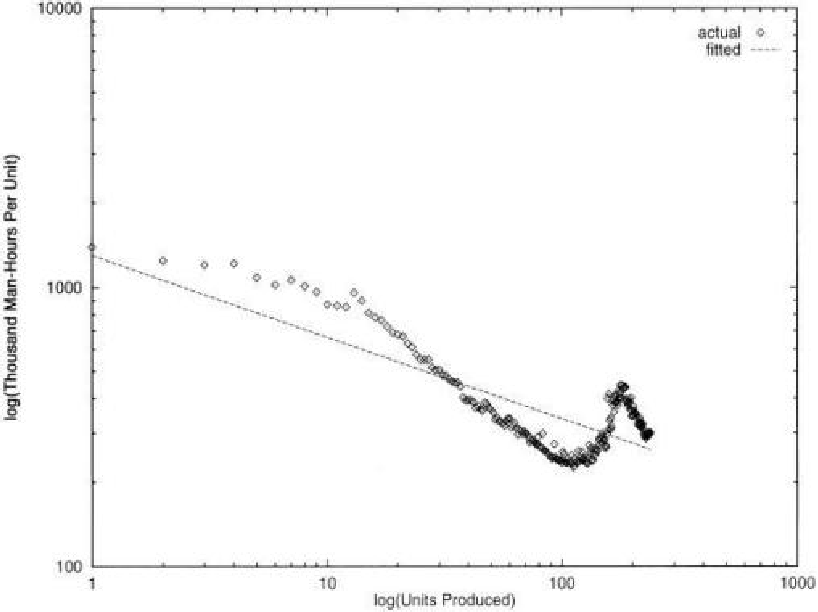
Results (no forgetting)

Table 1—Traditional Learning Model Regressions

	ln A	θ	γ_0	γ_1	Time	Adj.+	Adj.−	SSR	ρ_ε	L.R.
Basic regressions										
1. Units 1–112	7.90	−0.51	—	—	—	—	—	1.36	0.73	30%
	(0.06)	(0.01)							(0.04)	
2. Units 1–238	7.16	−0.29	—	—	—	—	—	15.0	0.97	18%
	(0.08)	(0.02)							(0.02)	
Line speed										
3.	6.51	−0.35	0.95	−0.20	—	—	—	11.0	0.92	21%
	(0.21)	(0.02)	(0.17)	0.03					(0.03)	
Calendar time										
4.	6.03	−1.08	−0.04	0.004	1.16	—	—	5.4	0.56	53%
	(0.15)	(0.04)	(0.13)	(0.025)	(0.07)				(0.04)	
Adjustment cost										
5.	6.75	−0.31	0.67	−0.16	—	0.07	−0.04	15.8	0.43	19%
	(0.26)	(0.03)	(0.25)	(0.05)		(0.03)	(0.02)		(0.06)	
N = 238	TSS = 33.7									

Notes: All regressions are 2SLS. Instruments (Z_i) are present and lagged demand shifters (various world GDP measures, the price of oil, and a time trend; see text) and present and lagged cost shifters (U.S. wage rate, aluminum price). L.R. is the implied learning rate.

Results (no forgetting)



Testing the Production Function

TABLE 2—TRADITIONAL LEARNING MODEL REGRESSIONS: INPUT PRICES AND DISECONOMIES OF SCOPE

	$\ln A$	θ	γ_0	γ_1	Wage	P_{AL}	P_{oil}	Scope	SSR	ρ_ε	L.R.
Diseconomies of scope											
6.	7.35	−0.49	0.49	−0.10	—	—	—	0.55	2.4	0.70	29%
	(0.10)	(0.01)	(0.08)	(0.02)				(0.02)		(0.04)	
Oil price											
7.	5.88	−0.54	1.36	−0.27	—	—	0.27	—	9.3	0.83	32%
	(0.21)	(0.03)	(0.17)	(0.03)			(0.04)			(0.04)	
Input prices											
8.	−15.9	−0.52	0.45	−0.09	8.68	0.50	—	—	10.0	0.81	30%
	(3.37)	(0.03)	(0.18)	(0.03)	(1.32)	(0.09)				(0.04)	
$N = 238$	$TSS = 33.7$										

Notes: All regressions are 2SLS. Instruments (Z_i) are present and lagged demand shifters (various world GDP measures, the price of oil, and a time trend; see text) and present and lagged cost shifters (U.S. wage rate, aluminum price). L.R. is the implied learning rate.

- (6) tests diseconomies of scope (plausible)
- (7–8) test for Cobb-Douglas (sign on wage is wrong)
- Can we do better than just a scope dummy?

Fitting the General Learning Model

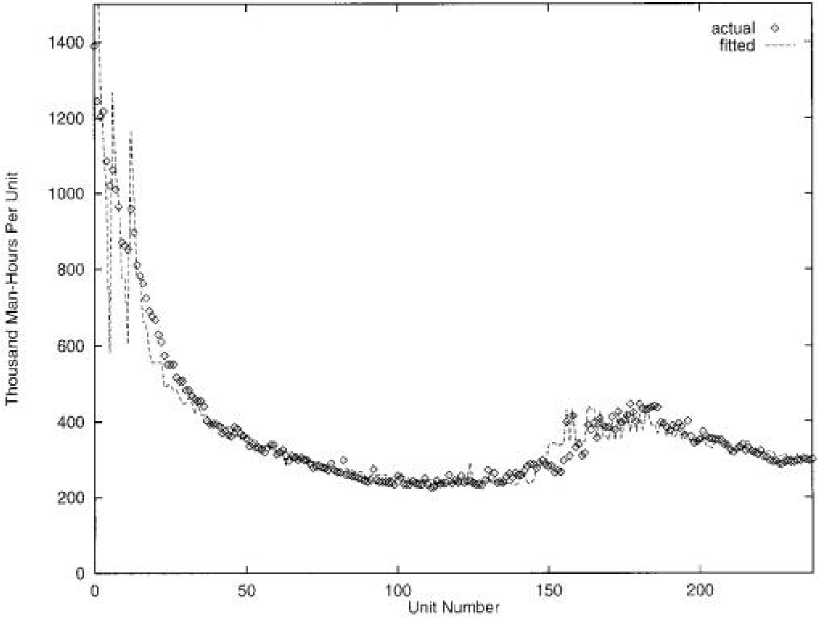
TABLE 3—GENERAL LEARNING MODEL REGRESSIONS

	$\ln A$	θ	γ_0	δ	λ	SSR	GMM(p)	ρ_ε	L.R.
OF only									
9. $[S_N^* = 9.3]$	7.63	−0.65	0.14	0.952	—	2.9	0.60	0.51	36%
	(0.01)	(0.02)	(0.12)	(0.003)				(0.05)	
Spillovers									
10. $[S_N^* = 6.9]$	7.73	−0.63	0.11	0.960	0.70	2.3	0.62	0.45	36%
	(0.01)	(0.03)	(0.17)	(0.003)	(0.07)			(0.05)	
$N = 238$	$TSS = 33.7$								

Notes: All regressions in this table use the HAC-IV method described in the text. Instruments (Z_i) are present and lagged demand shifters (various world GDP measures, the price of oil, and a time trend; see text) and present and lagged cost shifters (U.S. wage rate, aluminum price). S_N^* is the optimal bandwidth used in estimating the GMM covariance and optimal weight matrices. L.R. is the implied learning rate.

- Adding deprection causes SSR to fall $12.9 \rightarrow 2.9$, and $\delta \neq 1$
- Adding the spillover parameter λ increases δ
  - This accounts for some of the confounding effects of the introduction of the -500 series

Fitting the General Learning Model



General Learning Model

- Fits both halves of the data
- Outperforms the diseconomies of scope model from unit 140 onwards
  - Captures -500 production becoming less efficient, and the increasing labor requirements for -1 planes
- Implied depreciation rate $\delta = 0.96$ means that a firm "forgets" 39% of its knowledge in a year
  - Note that the definition of forgetting is *very* specific—it's only looking at a narrow type of human capital
- Allowing for depreciation increases the learning rate to 35%–40%
- λ is always significant and never equal to 1; reject perfect spillovers

Results

Take $\lambda = 0.70$ and $\theta = 0.63$

- The first -500 required 25% more labor than a -1
- Producing both -500s and -1s in similar numbers would have increased labor requirements by 11%
- Introducing a similar model can cause a setback in learning and an increase in variable costs
- Simultaneous production of multiple models can be meaningfully more expensive (without accounting for R&D)

Takeaways

- Production dynamics in the airplane manufacturing industry are *not* smooth; they're actually pretty complex.
- So far, we have only seen forgetting in industries that produce labor intensive products, with a lot of learning at the individual level, and high turnover.
  - Aircraft manufacturing, ship building, service franchises
  - Don't blindly start using this model everywhere
- **Stochastic interpretation:** estimating a stochastic learning model yields very similar results
  - Can think of learning as stochastic at the individual task level
  - Unit-level data, while still pretty granular, aggregates over this uncertainty so the model is approximately deterministic