Beyond Anderlohr: An Alternative Approach To Estimating Production Gaps

2016 ICEAA Professional Development & Training Workshop - Atlanta

Brent M. Johnstone

7 June 2016

Introduction

- **Production breaks interrupt the continuous flow of manufacturing and cost improvement**
- **Estimating the cost impact of these production interruptions remains a challenge**
- **In 1969 George Anderlohr released his paper on "What Production Breaks Cost"**
- **Anderlohr methodology is widely accepted as a "best practice" in the estimating community**
- **But is there a better way?**

Anderlohr & Elements of Learning

Anderlohr methodology identifies 5 elements of learning:

- **Personnel learning**
  - Learning lost when shop employees move to other programs or leave the company
  - Workers who return to line upon restart lose some physical dexterity ("muscle memory") and their familiarity with the product itself
- **Supervisory learning**
  - Some supervisors will move to other programs or leave company
  - Returning supervisors will be less familiar with old jobs & will have no knowledge about personalities and capabilities of new hires
- **Continuity of production**
  - Physical location and position of the production line – the relation of one work station to another, the location of tools, bins, parts, et al.
  - Production line balance
  - Suffers the greatest initial loss since initial discontinuities in parts production will create line imbalances and non-optimal work flows

Elements of Learning (cont'd)

- **Methods**
  - Production planning and associated knowledge of how to build parts and assemblies
  - Restarts usually require incorporation of engineering changes since previous production, which in turn create re-learning
- **Tooling**
  - Loss, damage or intentional destruction of tools
  - Transition from temporary "soft" tools to more permanent "hard" tooling, forcing relearning and "proofing out" of the new tools

Example – Anderlohr Calculation

What % of production personnel will return to the program at restart? What % of tooling will be available at restart?

Of the personnel who return, how much of their knowledge will they retain at restart?

Element of Learning	Element Weighting	x	Percent Available	x	Percent Learning Retained	=	Weighted Learning Retained
Production Personnel Learning	20%		75%		67%		10%
Supervisor Personnel	20%		75%		67%		10%
Continuity of Production	20%		0%				0%
Methods Improvement	20%		90%				18%
Special Tooling	20%		60%				12%
Grand Totals	100%						50%

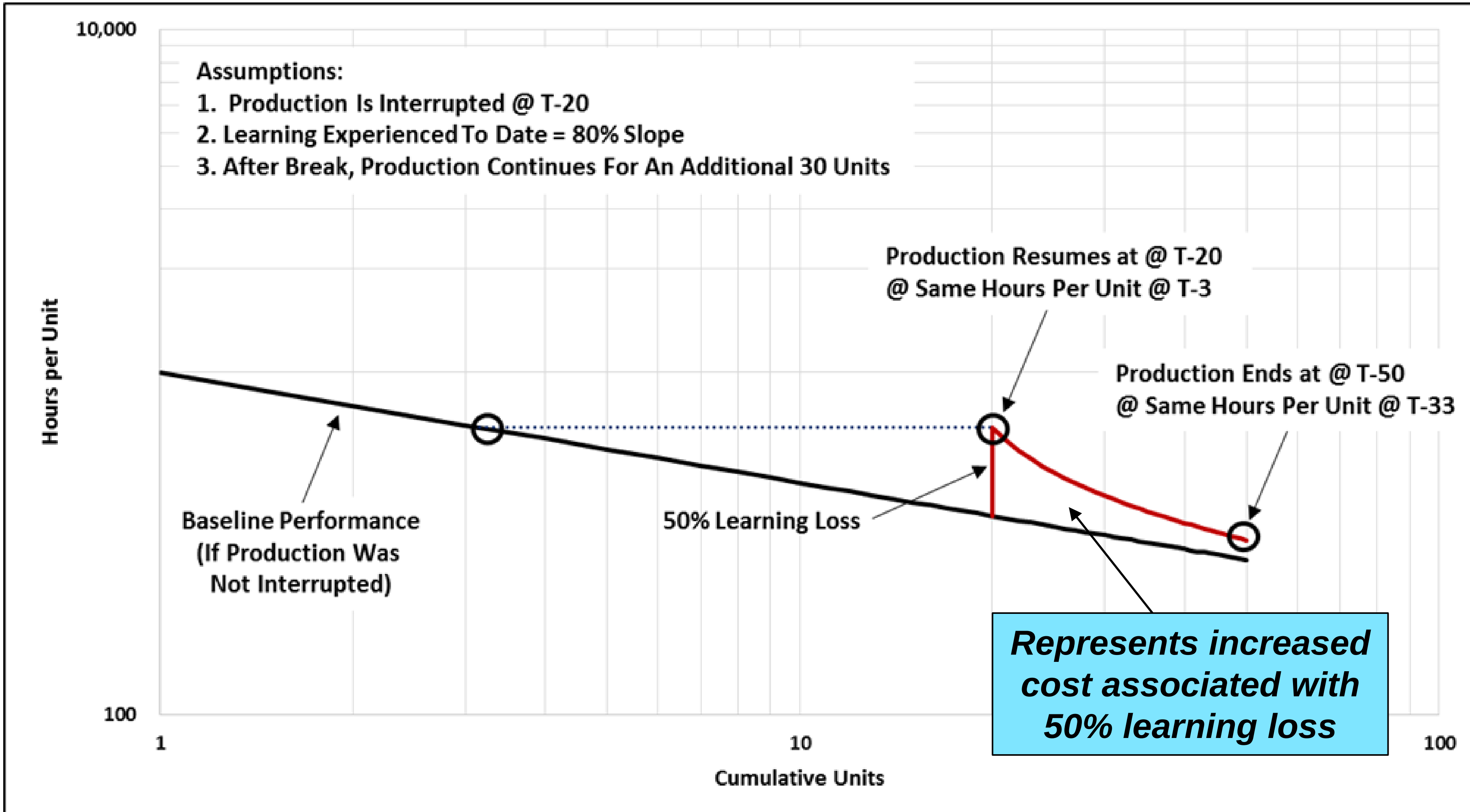
Learning Lost = 1 - % Learning Retained 50%

Each element needs to be weighted for its contribution to the total

Weighting & estimated values are multiplied across to calculate percent learning retained

Learning loss is 1 - percent learning retained

Application of Learning Loss



Objections to Anderlohr

- **Weighting of elements of learning is usually arbitrary**
- **Often difficult to determine the percent of personnel, planning and tools available, particularly in an informal study environment**
- **Percent of learning retained (or lost) due to a break is often arbitrary**
- **Bottom line: Anderlohr methodology requires extensive degree of judgment**
- **Given the same set of facts, it is likely 2 different analysts will derive different estimates**
- **Is there a more empirically-based methodology to help us determine cost impact of a cost break?**

Organizational Learning & Forgetting

- **Recent research on "organizational forgetting" opens the possibility of an empirically-based approach to estimating production breaks**

- **Of interest is Lamar Benkard's study of learning and forgetting on the L-1011 commercial jetliner program**

- **Benkard's paper proposes the phenomenon of "organizational forgetting," where production experience depreciates over time**
  - **"Organizational forgetting is the hypothesis that a firm's stock of production experience depreciates over time. Since an aircraft firm's experience is embodied in its workers, it seems likely that turnover and layoffs may lead to losses of experience. The traditional learning hypothesis does not allow for this possibility." (Benkard, 2000, pg. 1036.)**

Organizational Learning & Forgetting

- **As personnel move in and out of a program, as the production line is altered and the continuity of the production line ebbs and flows, as tools and methods change over time, the accumulated learning over time is depreciated**

- **This forgetting occurs all the time, but provided a constant design configuration and production rate is maintained, it is disguised by the traditional learning curve**
  - **"The firm's experience is not being fully retained over time, which only becomes apparent when production rates are uneven and new models are introduced." (Benkard, 2000, pg. 1046.)**

Organizational Learning & Forgetting

- Mathematically, traditional learning is defined as:

$$\ln L_i = \ln A + \theta \ln E_i$$

L_i is labor hours per unit,
A is the theoretical first unit cost,
E is cumulative quantities produced to date
θ is the coefficient of learning

- To incorporate organizational forgetting, Benkard proposes variable E be redefined as cum quantity and ***time***:

$$E_t = \delta E_{t-1} + q_{t-1}$$

t is time (measured from first flight)
δ is the coefficient for learning retention
q is cumulative time-depreciated experience for prior production units

- By definition, $0 \le \delta \le 1$ (if $\delta = 1$, there is no organizational forgetting…100% of learning is retained over time)

Organizational Learning & Forgetting

- **Conventional learning theory holds each unit built in the past contributes knowledge toward building the product and knowledge is not discounted over time**

- **Benkard's theory holds the opposite – knowledge attained through prior build *is* degraded over time**
  - **"An implication of the organizational forgetting hypothesis is that recent production is more important than more-distant past production in determining a firm's current efficiency. This prediction is perhaps more intuitive than that of the learning hypothesis, which treats all production equally no matter how old. In a practical example, it is hard to imagine that Boeing's rapid production of 747s in the early 1970's is as important to current unit costs as production in the early 1990's, particularly because it is unlikely that many of Boeing's workers from that period remain with the company today." (Benkard, 2000).**

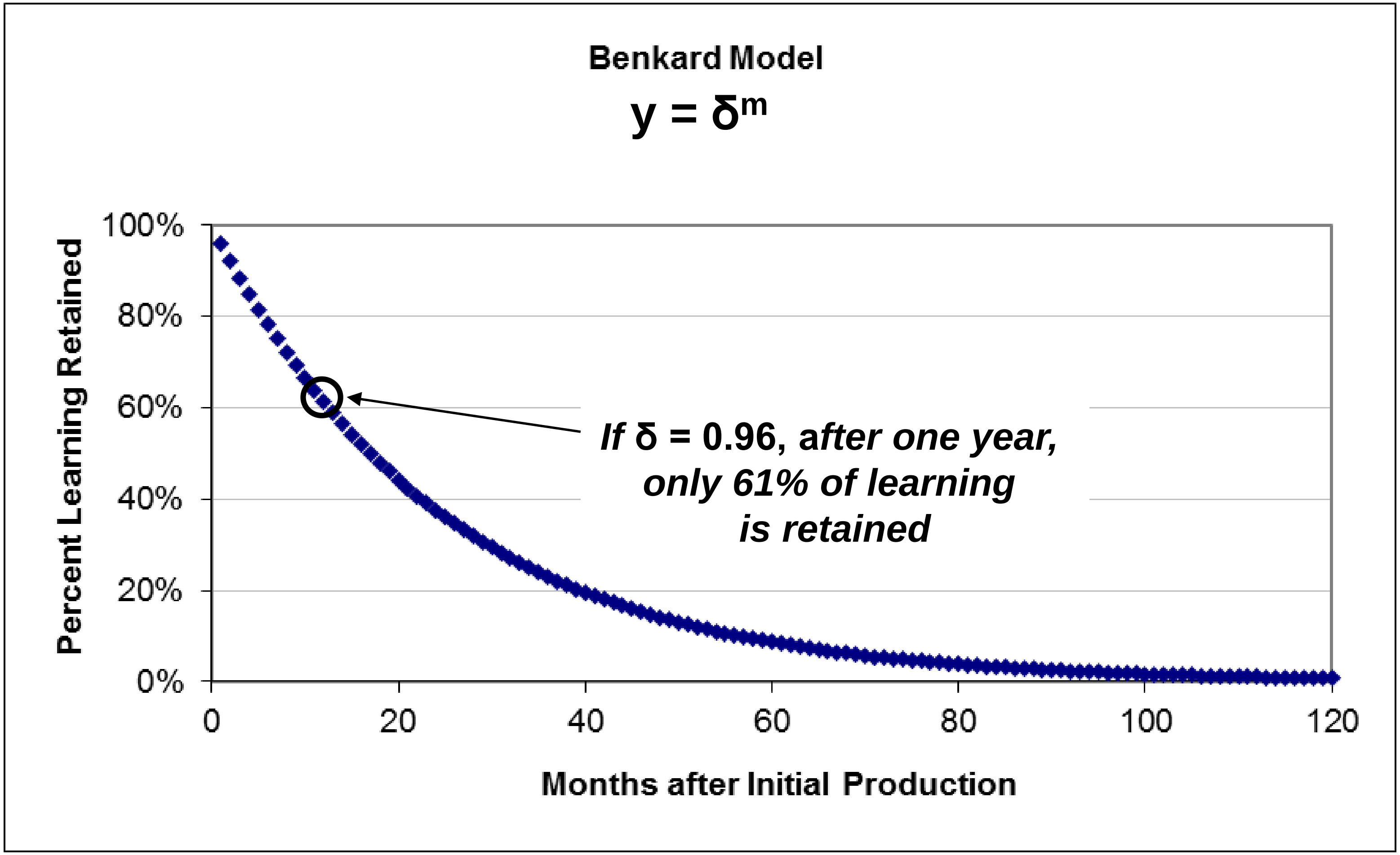
- **Per Benkard, experience depreciates at a constant rate:**

$$y = \delta^m$$

y = percent of learning retained
δ = coefficient for learning retention
m = number of months that have passed

Learning Retention Over Time

- **A production gap emerges as a special case in Benkard's theory when traditional learning ceases as production rates fall to zero**



Learning Retention Over Time

- **Logical that lost learning is directly related to passage of time**
- **Relationship is probably <u>not</u> linear**
  - **Certain elements of learning (methods improvement, tooling) are not lost as quickly as operator skill and proficiency**
  - **Most of the lost learning occurs relatively early**
  - **But there is still a substantial degree of learning retention even after two years**
- **Asymptotic shape of the curve seems to tie back to our understanding of cost improvement**
- **Only after many years pass does the learning retention eventually degrade to zero**

Values of δ (Learning Retention)

δ	% Learning Retained After One Year (δ^{12})	% Learning Lost After One Year (1 - δ^{12})
0.80	7%	93%
0.85	14%	86%
0.90	28%	72%
0.95	54%	46%
0.99	89%	11%

- **Theoretically, δ must be between $0 < \delta < 1$.**
- **More probably, it lies between $0.90 < \delta < 1$**
- **Difficult to believe under normal rate of employee turnover that 75%-95% of learning is lost in a single calendar year (if $\delta < 0.90$)**
- **Such low learning retention does not correspond to most cost estimators' experience**

Published Values of δ (Learning Retention)

Author	Value of δ	Source Data
Argote, et al. (1990)	0.75	World War II Liberty ship build, monthly data
Benkard (2000)	0.96	L-1011 aircraft build, unit data
Thompson (2006)	0.943 – 0.964	World War II Liberty ship build, unit data

- Argote, Linda, Sara L. Beckman, and Dennis Epple (1990). “The Persistence and Transfer of Learning in Industrial Settings,” Management Science, vol. 36, no. 2, February 1990, pgs. 140-154.
- Benkard, C. Lanier (2000). “Learning and Forgetting: The Dynamics of Aircraft Production,” American Economic Review, September 2000, pgs. 1034-1054.
- Thompson, Peter (2006). “How Much Did The Liberty Shipbuilders Forget?” Department of Economics, Florida International University, Miami, Florida.

- Previously published academic research puts δ between 0.75 and 0.96
- Two ways to establish value of δ
  - Regression of historical cost data (Method 1)
  - Fitting δ to observed interruption data (Method 2)

Method 1: Regressing Historical Data

- History from recent military aircraft
  - Due to proprietary nature of this data, this program is not specifically identified
  - Aircraft is of conventional aluminum manufacture
  - A significant model upgrade occurred approximately three-quarters through the time line
  - Original model will be referred to Model A; the upgrade as Model B
- The variable t (time) is measured by months from the first aircraft delivery, where 1 = first month of aircraft deliveries.
- Consistent with Benkard's modeling for the L-1011, an additional variable λ has been introduced to account for experience that "spills over" from model A to model B

Regression of Historical Data (cont'd)

- **Definition of experienced units E for models A and B are defined as follows:**

$$E_{A,t} = \delta E_{A,t-1} + q_{A,\ t-1} + \lambda q_{B,\ t-1} \qquad \text{and } E_{A,1} = 1$$

$$E_{B,t} = \delta E_{B,t-1} + q_{B,\ t-1} + \lambda q_{A,\ t-1} \qquad \text{and } E_{B,1} = 1$$

(Experience in a given month is the cumulative depreciated experience of all units that took place prior)

- **If $\delta = 1$ and $\lambda = 1$, then our regression equation collapses back to our standard learning equation, allowing us to use ordinary least squares (OLS) regression**

- **If $\delta \neq 1$ and $\lambda \neq 1$, then we are now dealing with a nonlinear regression equation**
  - **We will need to estimate the values of δ and λ consistent while at the same time minimize the sum of squared residuals (SSR)**

Nonlinear Estimation

- **Nonlinear estimation can be performed with a number of statistical software packages such as SAS, R, et al.**

- **Good news is we can achieve the same result using Microsoft Excel Solver**
  - **Not everyone has access to high-powered statistics packages**
  - **All estimators are familiar with Excel**

Step One (Ordinary Least Squares)

- **If we set δ and λ to 1, Microsoft Excel returns coefficients for A and θ consistent with OLS using Excel functions INTERCEPT and SLOPE, and calculates sum of squared residuals (SSR):**

Intercept	Masked
Seq (E)	Masked
DELTA	1.00
LAMBDA	Masked

INTERCEPT(J13:J48,K14:K48)

SLOPE(J13:J48,K14:K48)

Optimize these values in order to...

...minimize this

SSR 1.71

Model	Hrs (K)	Months Since First Delivery (1st Unit = 1) A	Months Since First Delivery (1st Unit = 1) B	Time-Adjusted Sequence (E) A	Time-Adjusted Sequence (E) B	ln (y)	ln (E)	Predicted	Residual	SSR
A	Masked	1	0	1.0	-	Masked	-	Masked	0.14	0.02
A		2	0	4.0	-		1.39		(0.05)	0.00
A		4	0	6.0	-		1.79		(0.07)	0.01
A		7	0	8.0	-		2.08		(0.07)	0.01
A		10	0	9.0	-		2.20		(0.10)	0.01
⋮		⋮	⋮	⋮	⋮		⋮		⋮	⋮
B		89	1	901.0	1.0		6.80		(0.79)	0.63
B		94	5	945.0	5.0		6.86		(0.53)	0.28
B		97	8	973.0	25.0		6.91		(0.22)	0.05
B		101	12	983.0	60.0		6.95		(0.09)	0.01
B		105	16	997.0	105.0		7.00		(0.07)	0.00
B		109	20	1,003.0	165.0		7.06		(0.12)	0.01
B		114	25	1,003.0	231.0		7.12		(0.21)	0.04

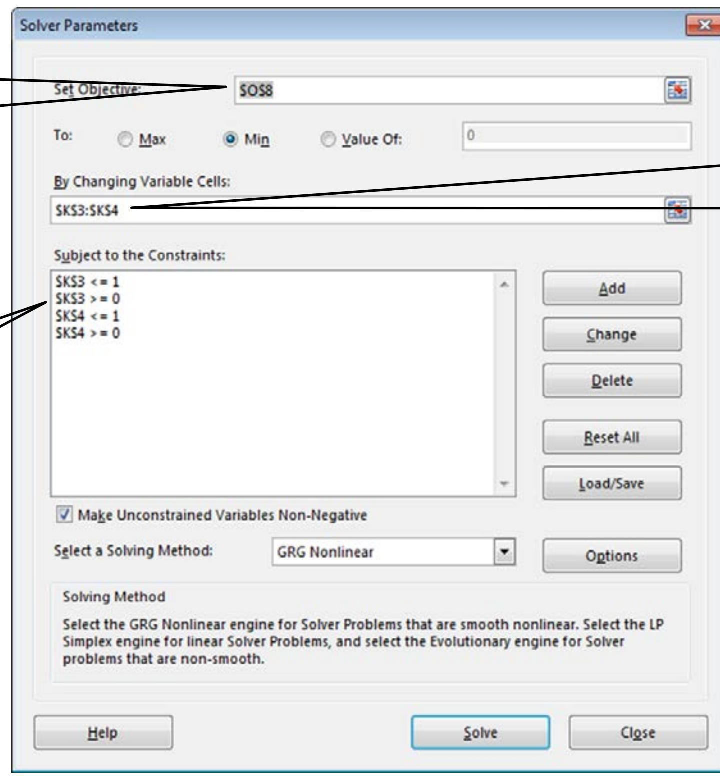
Microsoft Excel Solver

- **The next step is to allow δ and λ to vary in order to determine which values will minimize SSR**
- **Solver allows us to minimize SSR by changing δ and λ subject to the constraints that 0 < δ < 1 and 0 < λ < 1**

OBJECTIVE (Minimize SSR)

CHANGING VARIABLES (δ and λ)

CONSTRAINTS (0 < δ < 1 and 0 < λ < 1)



Step Two (Minimize SSR)

- **While Solver determines the optimal values for δ and λ, Excel functions INTERCEPT and SLOPE are simultaneously calculating the best fit coefficients for A and θ:**

SOLVER determined these values...

Intercept	Masked
Seq (E)	Masked
DELTA	0.93
LAMBDA	Masked

These values also recalculated by Excel as a result of different values for DELTA and LAMBDA

...will minimize this

SSR 0.52

		Months Since First Delivery (1st Unit = 1)		Time-Adjusted Sequence (E)						
Model	Hrs (K)	A	B	A	B	ln (y)	ln (E)	Predicted	Residual	SSR
A	Masked	1	0	1.0	-	Masked	-	Masked	0.30	0.09
A		2	0	3.9	-		1.37		(0.03)	0.00
A		4	0	5.4	-		1.69		(0.06)	0.00
A		7	0	6.4	-		1.85		(0.04)	0.00
A		10	0	6.2	-		1.82		(0.02)	0.00
⋮		⋮	⋮	⋮	⋮		⋮		⋮	⋮
B		89	1	230.8	1.0		4.18		(0.33)	0.11
B		94	5	206.4	4.8		4.13		(0.03)	0.00
B		97	8	195.2	23.9		4.36		0.21	0.04
B		101	12	157.3	53.0		4.57		0.26	0.07
B		105	16	132.8	85.0		4.80		0.21	0.05
B		109	20	106.2	124.2		5.04		0.09	0.01
B		114	25	74.7	153.4		5.16		(0.03)	0.00

Comparison of Regressions

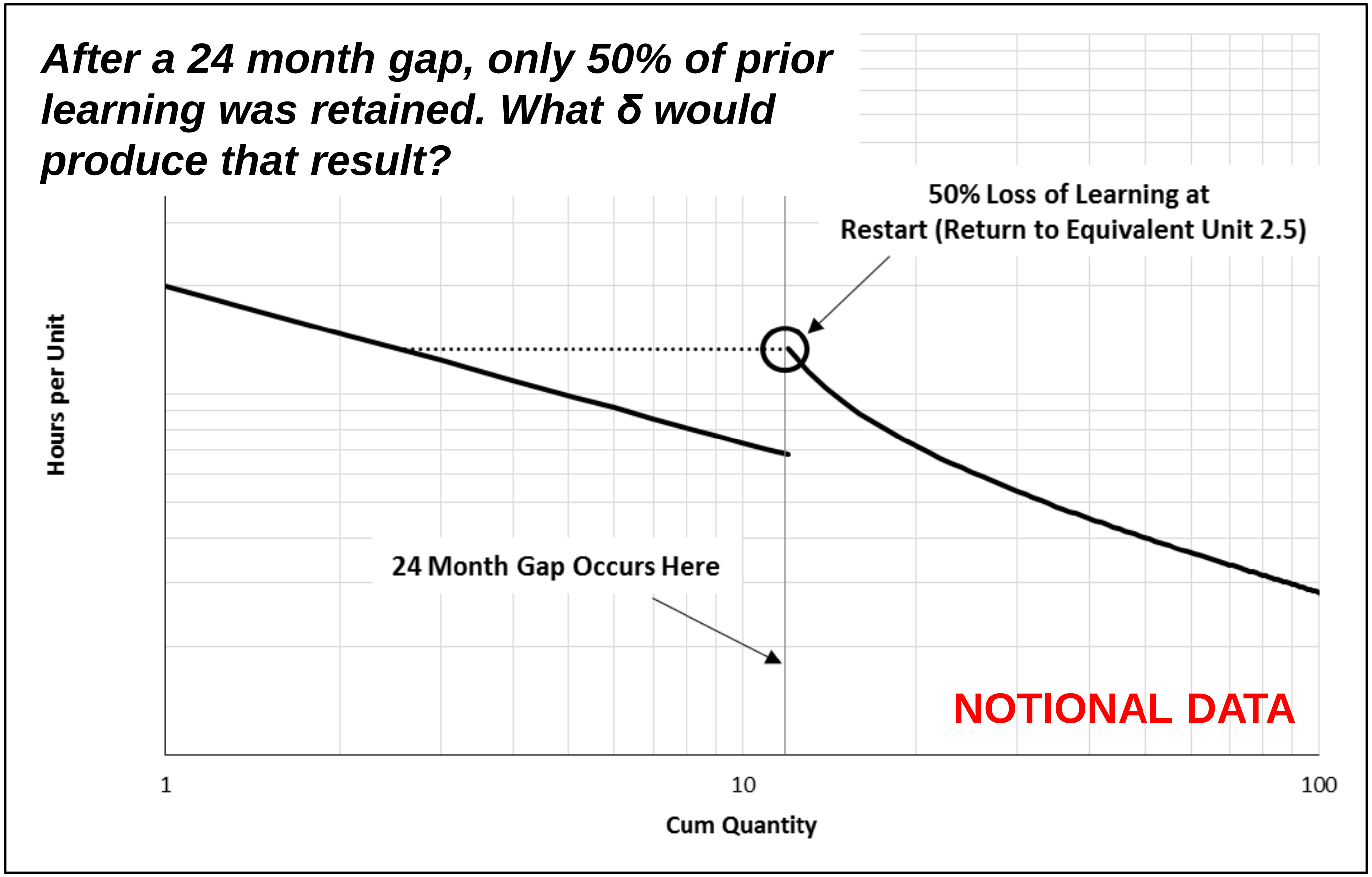
- **It can be seen that the organizational forgetting model where δ ≠1 and λ ≠ 1 has a better set of fit statistics than the traditional learning model**

	Traditional Learning	O.F. (δ, λ ≠ 1)
N	36	36
Intercept	Masked	Masked
Slope	Masked	Masked
δ (Learning Retention)	N/A	0.93
λ (Experience Spillover)	N/A	Masked
R-Square	86%	96%
SEE	23%	12%
F-Statistic	211.6	809.6
SSR	1.78	0.52

- **Derived value δ = 0.93 is below Benkard and Thompson, but within our proposed range of reasonableness (δ > 0.90)**

Method 2: Fitting δ To Observed Gap

- Second method to determine δ is fit it to an observed historical production gap



Method 2 (cont'd)

- **Solving for δ, we take the natural logarithm of both sides:**

$$\delta^{24} = 0.50$$

$$\ln(\delta^{24}) = \ln(0.50)$$

$$24 \ln \delta = \ln(0.50)$$

$$\ln \delta = -0.02888$$

$$\delta = 0.97$$

24 month gap
50% learning retention

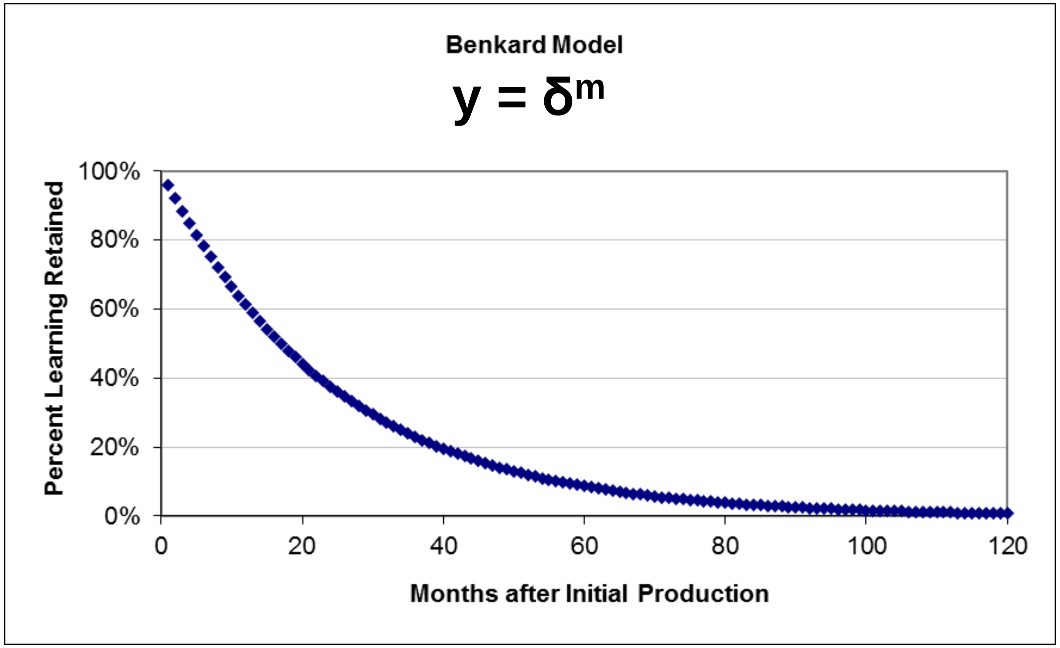
- **Allows us to use historical experience from prior production interruptions**

- **If several examples of production breaks can be constructed, it could empirically determine the impact of programmatic events**
  - **i.e., a transition from soft to hard tooling or a relocation of the physical production line.**

Learning Loss Table (Using Method 1 or 2)

- **Once δ is established, a table can be built showing learning retained and the length of production gap in months**

$\delta = 0.96$	Learning	
Months	Retained	Lost
1	96%	4%
2	92%	8%
3	88%	12%
4	85%	15%
5	82%	18%
6	78%	22%
12	61%	39%
24	38%	62%
36	23%	77%
48	14%	86%



- **Once we know percent learning loss, we calculate a new position on the learning curve and proceed down the curve in an asymptotic recovery to the baseline**

Potential Advantages

- Empirically based
- Eliminates the use of estimating judgment inherent in the Anderlohr methodology.
- More defensible to a hostile audience
- More likely to produce an answer agreeable to both parties in a negotiation
- Logically correlate learning loss to the length of the interruption, making it easier to determine the cost impacts of different production schedule scenarios

Areas For Future Research

- Additional estimates of the learning retention variable δ
  - Is it sufficiently stable to warrant use to estimate production gap impacts?
  - Demonstrate robustness of δ across programs

- Estimated δ could be applied retrospectively to historical production gap estimates to validate that it produces reasonable values

- Is δ is more reliably determined by regressing historical actuals or by calculating it based on prior production interruptions?

References

- Anderlohr, George (1969). "What Production Breaks Cost," Industrial Engineering, September 1969, pgs. 34-36.
- Argote, Linda, Sara L. Beckman, and Dennis Epple (1990). "The Persistence and Transfer of Learning in Industrial Settings," Management Science, vol. 36, no. 2, February 1990, pgs. 140-154.
- Benkard, C. Lanier (2000). "Learning and Forgetting: The Dynamics of Aircraft Production," American Economic Review, September 2000, pgs. 1034-1054.
- General Accounting Office (2009). GAO Cost Estimating and Assessment Guide, Washington, DC: GAO-09-3SP.
- Mislick, Gregory and Daniel A. Nussbaum (2015). Cost Estimating: Methods and Tools, Hoboken, New Jersey: John Wiley & Sons.
- Thompson, Peter (2006). "How Much Did The Liberty Shipbuilders Forget?" Department of Economics, Florida International University, Miami, Florida.