Learning Curves vs. Rate Curves
What’s the Difference and Why Does it Matter?

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Learning Curves vs. Rate Curves
What’s the Difference and Why Does it Matter?

OUTLINE

• Definitions – What they are
  • Learning curves
    • Experience curves
  • Rate curves
    • Fixed and variable cost
    • Lot buys

• Applications – Why it matters
  • Differences in application and results
  • Example
Learning Curves vs. Rate Curves
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DEFINITIONS – Learning Curves

• Traditional definition of learning curves

  • In summary: Unit cost is reduced by “x”% every time cumulative units produced doubles:
    • Unit Cost\(_n\) = Theoretical First Unit (TFU) \times Unit\(_n^b\)
      • Where \(b = \ln(\text{learning curve } \%) / \ln(2)\)

  • History: T. P. Wright (1936), "Factors Affecting the Cost of Airplanes"

• Two types: Unit (Crawford) and Cumulative Average (Wright)
  • Specific unit cost resulting from Crawford approach = cumulative average unit cost Wright approach
  • Cumulative Average or Specific Unit cost Crawford > same Unit cost Wright
Some level of disagreement regarding definition and appropriate applications of “learning” curves

FROM: Office of the Deputy Director of Defense Procurement and Acquisition Policy for Cost, Pricing, and Finance:

Basic Improvement Curve Concept
You may have learned about improvement curves using the name learning curve analysis. Today, many experts feel that the term learning curve implies too much emphasis on learning by first-line workers. They point out that the theory is based on improvement by the entire organization not just first-line workers. Alternative names proposed for the theory include: improvement curve, cost-quantity curve, experience curve, and others. None have been universally accepted. In this text, we will use the term improvement curve to emphasize the need for efforts by the entire organization to make improvements to reduce costs.
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DEFINITIONS – Learning Curves

• Typically used to model/estimate labor hours ($’s)
  • Traditionally primarily applied to touch labor
  • With increasing automation touch labor now often less than 20% total production cost
    • E.g. Shuttle External Tank, touch labor intensive, ~ 15%


7.1.1 Situations for Use

The improvement curve cannot be used as an estimating tool in every situation. Situations that provide an opportunity for improvement or reduction in production hours are the types of situations that lend themselves to improvement curve application. Use of the improvement curve should be considered in situations where there is:

A high proportion of manual labor
Uninterrupted production
Production of complex items
No major technological change
Continuous pressure to improve
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DEFINITIONS – Experience Curves

• The Experience Curve
  • Bruce Henderson – Boston Consulting Group (1966)

  Cost of value added declines approximately 20 to 30 percent each time accumulated experience is doubled.

The name (Experience Curve) was selected to distinguish this phenomenon from the well known and well documented learning curve effect. The two are related, but quite different. … The so-called learning curve effect apparently had somewhat limited application, however. It only applied to direct labor. Unless the job changed, this meant the time required to obtain a given cost decline tended to double each cycle of experience. This masked the far reaching implication of the possibilities of job element management with volume changes.

• Basically an expansion of application of learning curve theory
  • Factors: Learning + Specialization + Investment + Scale
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DEFINITIONS – Rate Curves

• Same math as learning curve but describes different phenomena
  • Much closer to broader experience curve definition
  • Equation intercept (First Unit or TFU) is adjusted to production rate of one per year (“T1,1”)

• Cost behavior patterns as function of quantity and time
  • Learning curve independent variable (cumulative unit number) is time-independent
  • Rate curve variable is time-dependent
    • Number units produced in time period (e.g. per year)
    • Total number units produced over given time period (e.g. lot size)

• Key difference: Rate curves model fixed cost per time period plus variable (marginal) cost per unit produced
  • Learning curve equation does not account for fixed/variable cost behavior patterns over specific time periods
DEFINITIONS – Fixed Cost

• Fixed Cost
  • In the long term all costs are variable
    • “Fixed cost” assumes “on-going concern”: maintain capability to produce more in future time periods
    • Change in requirement reduces fixed cost ≠ variable cost - Reductions must be managed - Generally manifested as layoffs
  • The degree to which costs are fixed determines the efficiency of the system as operating conditions change
    • Large fixed costs in relation to variable costs mean total cost is insensitive to demand
    • Unit cost extremely sensitive to demand

• Aerospace high fixed cost driven by combination of unique requirements and low flight/production rates
  • Non-standard components, unusual labor skill sets, large dedicated facilities (e.g. MAF, VAB, Promontory)
DEFINITIONS – Fixed Cost

• Fixed Cost
  • Headcount is primary contributor (“Standing Army”)
    • Dedicated people producing at less than full capacity are essentially underutilized fixed assets
  • Unique skill requirements + labor-intense processes = high dedicated headcount
  • Not just the buildings/infrastructure
  • Legacy costs - defined retirement benefits costs increasing + shrinking business base = double whammy on rates

“The thing we need everyone to understand fully is that the Shuttle fixed costs are way more of a problem than the variable costs associated with a number of flights. That is why the very best thing for the Shuttle program, and for the transition we are planning to the next-generation system, is to know the date when we want to retire. Then we can work to that date. We may need to adjust the budget to accommodate flight rate, but that is less of an issue.”

Michael D. Griffin
Wednesday, August 31, 2005 6:50 PM
Learning Curves vs. Rate Curves
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DEFINITIONS – Recurring Cost

♦ Total Recurring Cost (TC):
  • The total cost to produce “n” units in a given time period (e.g. year)
  • Aka “Production & Operations cost”
  • \( = (\text{VC} \times \text{No. Units}) + \text{FC} \)

♦ Average Unit Cost (AUC):
  • Total Recurring Cost / No. Units
  • Aka “Cost per Unit (Flight)”
  • \( = \frac{\text{VC} + (\text{FC} \times \text{No. Units})}{\text{No. Units}} \)

♦ Variable Cost (VC):
  • Cost to produce +/- one unit
  • Aka “Marginal Cost”
  • NOT the same as AUC

♦ Fixed Cost (FC):
  • Cost incurred regardless of number units produced
  • Generally assumes “on-going concern”-maintains capacity for use in later time periods
  • Primarily “standing army”-people
  • Can include prime and subs
  • Can include incremental step function (new shift, 2nd line, etc.)
Learning Curves vs. Rate Curves
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DEFINITIONS – The “Rate Curve”

- Shuttle External Tank Production Cost
  - Cost per Year vs. Number Units Produced
  - Based on 2002 Op Plan

**External Tank Cost per Year**

### Total Cost per Year

\[ \text{Total Cost} = 14.487x + 205.88 \]

### Production Rate per Year

<table>
<thead>
<tr>
<th>Production Rate per Year</th>
<th>Total Cost per Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$0.00</td>
</tr>
<tr>
<td>2</td>
<td>$50.00</td>
</tr>
<tr>
<td>4</td>
<td>$100.00</td>
</tr>
<tr>
<td>6</td>
<td>$150.00</td>
</tr>
<tr>
<td>8</td>
<td>$200.00</td>
</tr>
<tr>
<td>10</td>
<td>$250.00</td>
</tr>
<tr>
<td>12</td>
<td>$300.00</td>
</tr>
</tbody>
</table>

\[ \frac{-0.7402}{\ln(2)} = \ln(0.60) \]

\[ \text{$/Unit} = 188.7M \times \text{Units/Yr}^{-.7402} \]

\[ \text{$/Year} = (188.7M \times \text{Units/Yr}^{-.7402}) \times \text{Units/Yr} \]

\[ 
\begin{align*}
\text{$/Year} &= ($14.5M \times \text{Units/Yr}) + 205.9M \\
\text{$/Unit} &= 14.5M + 205.9M/\text{Number Units}
\end{align*}
\]

**Note:** Assume no more learning effects
DEFINITIONS – Lot Buys

• Rate Curve approach also considers/models lot buy savings
  • Price as function of quantity procured
    • Usually “x” total units over “y” time frame
      • E.g. 10 per year for 5 years vs. 5 per year for 10 years
  • Reflective of fixed (one-time) + variable production cost
    • Setup, Special Tooling/Jigs & Fixtures, Computer Programming (e.g. Computer Numeric Control (CNC), 3-D Printing), Prototypes, etc.
    • Marginal cost to produce n+1 units is usually minimal relative to fixed set-up cost
  • Cost impacted by both total number of units and number of time periods
  • Not the same as Economic Order Quantity (EOQ)

“The EOQ formula applies to products offered at a single price; therefore, if different prices or discounts are offered by your supplier based on quantity purchased, do not use EOQ.”
http://www.sdcexec.com/article/10732246/how-to-make-eoq-relevant-again
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Why Does It Matter?

- Key causal differences influencing cost behavior patterns being modeled
  - Learning: “getting better at it”
    - Same production process done repetitively/improved; primarily impacts labor/touch labor; eventually minimal to no impact on unit cost; does not account for time
  - Rate: “utilization of fixed assets” (e.g. people)
    - Amortization of fixed cost over more/less units within time period
    - Lot buys and/or yearly production rates

- Requires different understanding/application of equation – Three examples
  1. Learning impacts create more efficiency, not lower total cost
  2. Consideration of fixed and variable cost behavior patterns
  3. Consideration of lot buy impacts
Learning Curves vs. Rate Curves
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Learning Impacts: Efficiency vs. Cost

- Observation: Learning impacts often create more efficiency, not lower total cost/headcounts
  - Reduced throughput time increases production capacity with same level of personnel/touch labor headcount

- Can result in same or greater total cost as production is ramped up
  - Lower unit cost (e.g. learning effect) because of increased rate
  - Increases total production cost as more units produced

- External Tank example – production rate versus total touch labor hours per year (see next chart)
  - Touch labor per unit exhibits ~ 76% Crawford curve for units 1-50
    - Units 1-6 are original ET, no Unit 7, Units 8+ are Lightweight
    - Total touch labor hours per year increase as production rate ramps-up
  - Total labor cost ramps up accordingly
  - Labor hours (and cost) per unit reduced
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Learning Impacts: Efficiency vs. Cost

- **External Tank Example**
  - Increased efficiency (i.e. “learning”) increases production capacity, does not reduce headcount/total cost

- Data supports 76% Crawford curve ($R^2 = .86$); 80% Wright ($R^2 = .96$)
- Cycle time essentially halved between units 8 (1st LWET) and 12; stabilized to within +/- 10% until Challenger
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Fixed/Variable Impacts

• External Tank Example
  • Comparison of analysis considering learning curve impacts only vs. rate impacts (CY 2002 $M)
  • Key Variables:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>TFU $/Year</td>
<td>223</td>
<td>NAFCOM 2002</td>
</tr>
<tr>
<td>Learn %</td>
<td>84%</td>
<td>94 Budget to OMB</td>
</tr>
<tr>
<td>Cumul Unit No.</td>
<td>111</td>
<td>ET Prod History</td>
</tr>
<tr>
<td>Total Recur $/Yr</td>
<td>300</td>
<td>ET POP Data</td>
</tr>
<tr>
<td>Total Prod Rate/Yr</td>
<td>6</td>
<td>ET POP Data</td>
</tr>
<tr>
<td>Variable $/ET</td>
<td>15</td>
<td>ET POP Data</td>
</tr>
<tr>
<td>Fixed $/Year</td>
<td>206</td>
<td>ET POP Data</td>
</tr>
</tbody>
</table>

• Evaluation Process:

1. Evaluate the total cost and unit cost for production of 2, 4, 6, and 10 units per year using just the learning curve information with no regard for rate effects.
2. Compare the results of (1) to the estimated cost using the fixed and variable costs derived from the ET calibration data.
3. Calculate the rate variable values (rate curve % and rate per year) which would bring the learning curve-only data in line with the calibration data and compare.
4. Calculate the T1,1 cost which supports all known data variable values and compare resulting equation to calibration data and learning curve-only calculations.
**External Tank Example – Steps 1 and 2**
1. Total cost at 6/year = $407M; unit cost = $68M
2. Actual cost = $300M; unit cost = $50M

- **Learning curve-only approach implicitly treats total cost as all variable.**
- **Overstates total and unit cost by 35% @ 6/Year.**
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Fixed/Variable Impacts

• External Tank Example – Steps 3 and 4

3. Rate Curve = 60%

4. T1,1 = $598M

Unit Cost = $598 x (111^b) x (6^c)

Where:

b = ln(.84)/ln(2)
and
c = ln(.60)/ln(2)

• Incorporation of both learning and rate effects properly models actual cost.
Lot Buy Impacts

- Lot Buy impacts can be substantial; are driven by, but different than fixed/variable impacts – “n” units over “y” time period
  - Independent sources suggest potentially substantial lot buy savings on material and subcontract cost

- Space systems data suggests cost savings (per unit) of between 10% and 30% or more are possible when lot size is increased from range of 3 - 4 to 7 – 12
- NAVSEA study* similar results
- EELV Block Buy of 35-50 “cores” over 5 years: savings reported at $4.4B relative to previous one-at-a-time approach

* “Observation of Production Rate Effect in Historical Cost of Weapon Systems”, W. Banks, R. Cosgray, T. Lawless (2016 ICEAA Conference, Atlanta, GA, June 2016)
Conclusions

- While utilized universally within the cost estimating community, learning curve theory is not always well defined and, as a result, not necessarily applied consistently and/or appropriately.

- As typically applied, learning curves are appropriate in some circumstances, but do not consider/account for other important cost behavior patterns.

- Application of learning curves alone without consideration of time and quantity [fixed and variable costs and lot buys] can (substantially) misestimate unit and total production costs.

- When estimating recurring production cost of multiple units, incorporation of both learning and rate curve approaches potentially provides more accurate representation of cost behavior patterns and, thereby, cost.