Projecting Future Costs with Improvement Curves: Perils and Pitfalls

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Perils of Improvement Curves

- **Improvement curves (aka "learning curves) are one of the cost estimator's most utilized tools**
- **But their usage is filled with perils and pitfalls**
  - **Need to come with a warning label**
- **This presentation reviews some of the most dangerous traps analysts can fall into:**
  - **Straight-line projection**
  - **Failure to account for differences in development versus production**
  - **Dangers of recovery slopes**
  - **Carelessness about designating the first unit**
  - **Using learning curve slopes alone to measure production line efficiency**

Straight-Line Projection

Straight-Line Projection

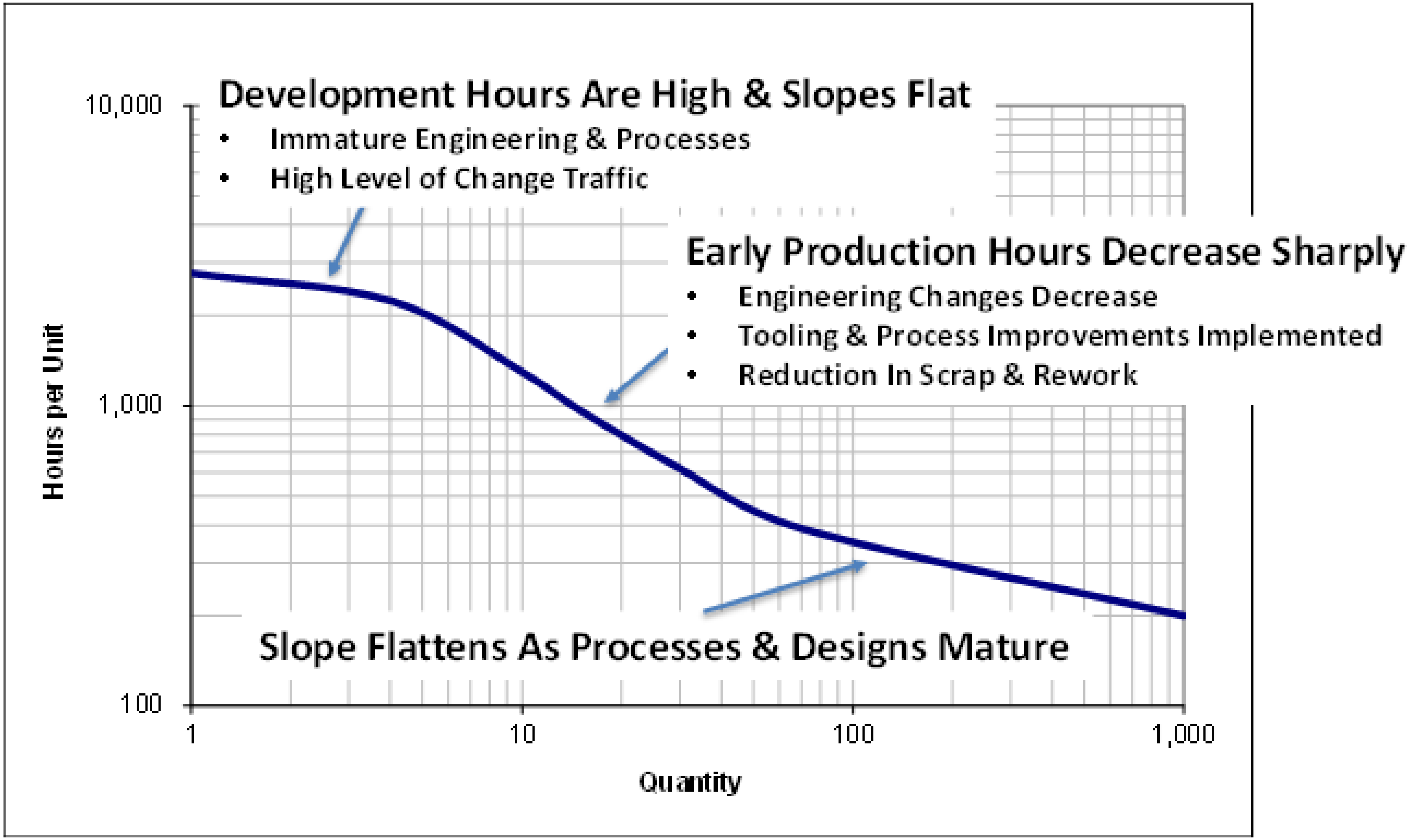
- **Analysts commonly regress historical data, calculate curve slope and then assume same slope to project cost of future work**
- **Often justified by R^2 – assumption being the higher the R^2 the "better" the model and more certain the future projection**
- **Can be referred to as the "straight edge and graph paper" school of estimating**
  - **Estimating the future is no more difficult than drawing a best fit on log-log paper and extending that line into the number of units being estimated**
- **What could be wrong with that?**

Straight-Line Projection

- **Quite a bit, in fact … studies have shown projecting from historical data is not a guarantee of success**
  - **"Predicting future progress rates from past historical patterns has proved unreliable." (Dutton, Thomas, 1984)**
  - **"Even with both an excellent fit to historical data (as measured by metrics like R^2), and meeting almost all of the theoretical requirements of cost improvement, there is no guarantee of accurate prediction of future costs." (RAND, 2008)**
  - **"…[E]ven projections based on producing an almost identical product over all lots, in a single facility, with large lot sizes, and no production break or design changes, do not necessarily yield reliable forecasts of labor hours. *Out-of-sample forecasting using early lots to predict later lots has shown that, even under optimal conditions, labor improvement curve analyses have error rates of about +/- 25 percent*." (RAND, 2008)**

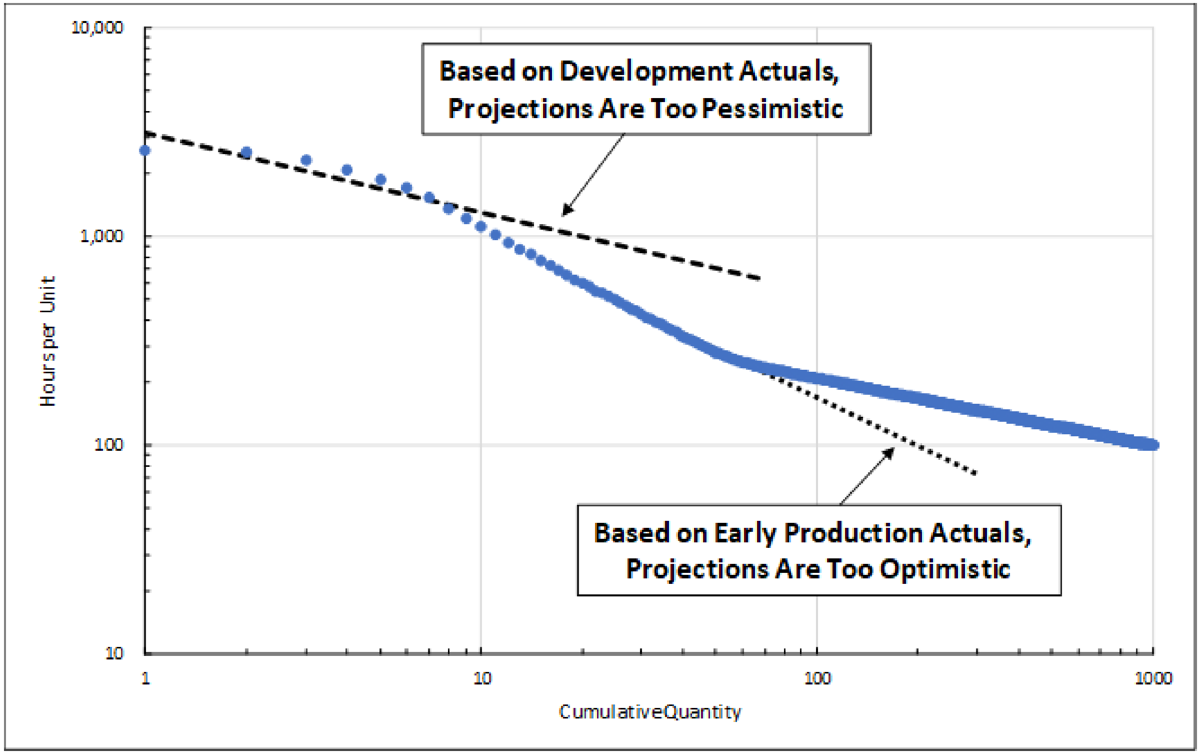
S-Curve

- ***The primary reason for this failure is the learning curve is not a straight line in log-log space over the product life cycle***



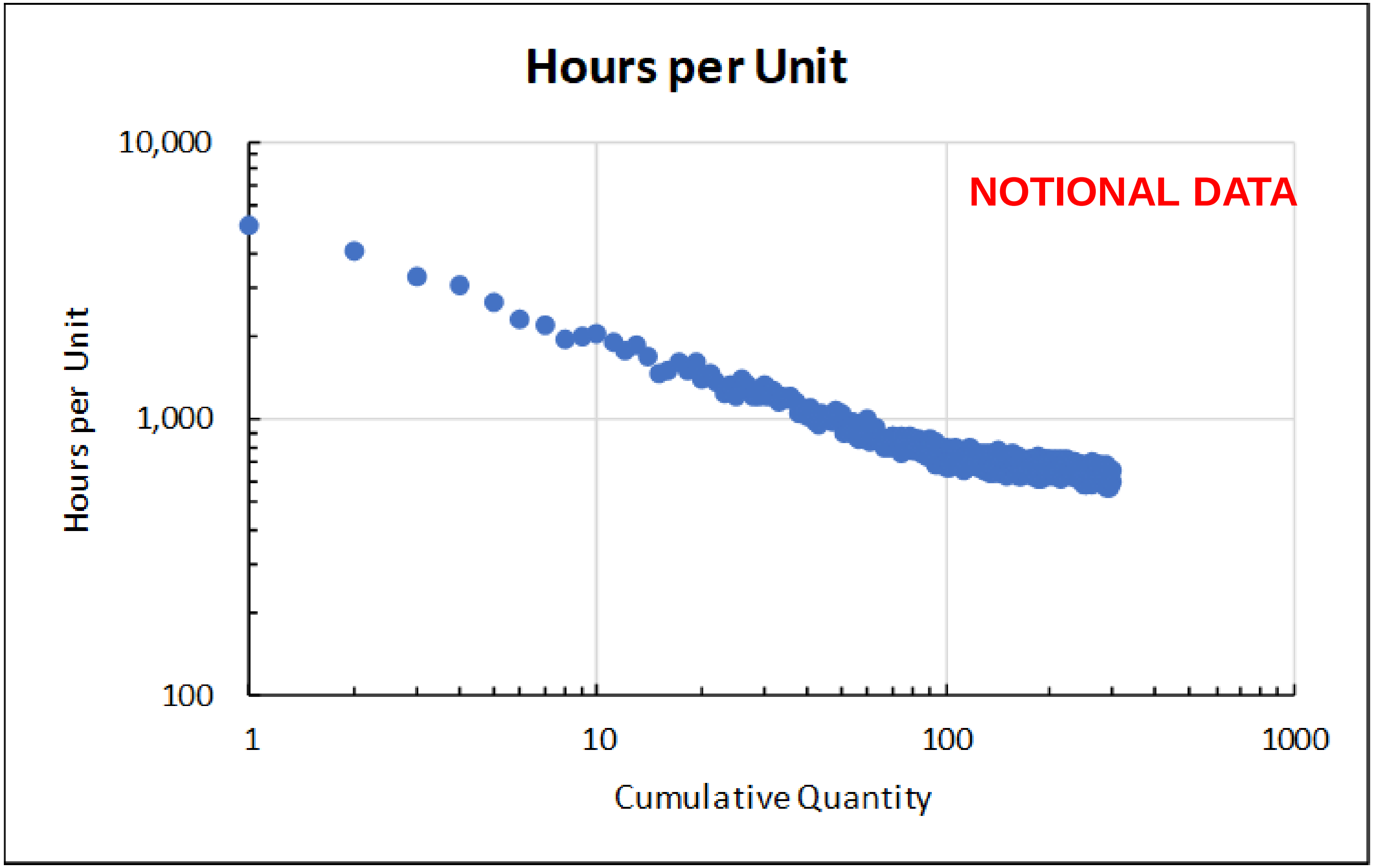
Actual Hours & S-Curve

- **Given reality of a S-curve, a straight-line projection based on actuals could overstate or understate the estimate depending on our sample**
- **Need to be aware of this when regressing data & be cognizant of what is really happening on the shop floor**



Regressing Data With A Break

- **What can we do when see an observed break in the learning curve slope in our actuals?**



Two-Leg Segmented Learning Curve

- To create a two-leg segmented learning curve, introduce breakpoint unit K
- Where Ln x < Ln K, we use our typical improvement curve equation:

$$\text{Ln } y = \text{Ln } \alpha_1 + \beta_1 \text{ Ln } x$$

- Where Ln x > Ln K:

$$\text{Ln } y = \text{Ln}(\alpha_1+\alpha_2) + \beta_2 \text{ Ln } x$$

- Where:
  - y = Manufacturing Hours per Unit
  - x = Cumulative Unit (Effective Sequence)
  - α_1 = Y-Intercept for Leg #1, Equal to Theoretical First Unit Hours for Leg #1
  - α_2 = Intercept Adjustment for Leg #2, Such That $\alpha_1 + \alpha_2$ Equals the Y-Intercept for Leg #2
  - β_1 = Rate of Learning for Leg #1, Such that 2^β Equals Learning Curve Slope #1
  - β_2 = Rate of Learning for Leg #2, Such that 2^β Equals Learning Curve Slope #2

Two-Leg Segmented Learning Curve

- **Example of how to set up our data**

					Dependent Variable	Independent Variables		
Unit	HPU	LN(Unit)	K	LN(K)	LN(HPU)	LN(β1)	LN(α2)	LN(β2)
1	5,020	-	101	4.62	8.52	-	-	-
2	4,065	0.69	101	4.62	8.31	0.69	-	-
3	3,248	1.10	101	4.62	8.09	1.10	-	-
4	3,038	1.39	101	4.62	8.02	1.39	-	-
5	2,628	1.61	101	4.62	7.87	1.61	-	-
6	2,272	1.79	101	4.62	7.73	1.79	-	-
7	2,216	1.95	101	4.62	7.70	1.95	-	-
8	1,949	2.08	101	4.62	7.58	2.08	-	-
9	2,001	2.20	101	4.62	7.60	2.20	-	-
10	2,030	2.30	101	4.62	7.62	2.30	-	-
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
99	682	4.60	101	4.62	6.53	4.60	-	-
100	668	4.61	101	4.62	6.50	4.61	-	-
101	798	4.62	101	4.62	6.68	-	1	4.62
102	677	4.62	101	4.62	6.52	-	1	4.62
103	724	4.63	101	4.62	6.59	-	1	4.63
104	692	4.64	101	4.62	6.54	-	1	4.64
105	680	4.65	101	4.62	6.52	-	1	4.65
106	746	4.66	101	4.62	6.61	-	1	4.66
107	799	4.67	101	4.62	6.68	-	1	4.67
108	724	4.68	101	4.62	6.59	-	1	4.68
109	763	4.69	101	4.62	6.64	-	1	4.69
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

PARTIAL DATASET

Regression Results

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.985
R Square	0.971
Adjusted R Square	0.970
Standard Error	0.058
Observations	300

Also allows us to compare a single R^2 value for multi-leg slope versus single leg slope

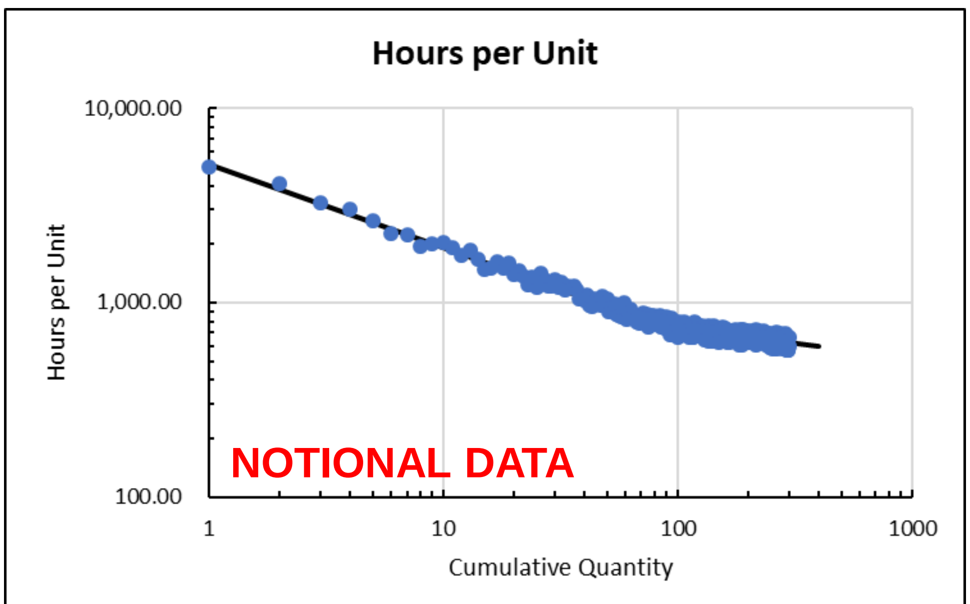
ANOVA

	df	*SS*	*MS*	*F*	*ignificance F*
Regression	3	32.35	10.78	3,249.08	0.00
Residual	296	0.98	0.00		
Total	299	33.33			

	Coefficients	*tandard Err*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*ower 95.0%*	*pper 95.0%*
Natural log - Intercept (ln α_1)	8.55	0.02	365.37	-	8.51	8.60	8.51	8.60
Natural log - Beta-1 (ln β_1)	(0.43)	0.01	(68.58)	0.00	(0.44)	(0.42)	(0.44)	(0.42)
Natural log - Alpha-2 (ln α_2)	(1.24)	0.07	(16.88)	0.00	(1.39)	(1.10)	(1.39)	(1.10)
Natural log - Beta-2 (ln β_2)	(0.15)	0.01	(11.57)	0.00	(0.18)	(0.13)	(0.18)	(0.13)

Results:

5,167	TFU for Leg #1
74.2%	Slope for Leg #1
1,495	TFU for Leg # 2
90.1%	Slope for Leg #2



Gives us:

Unit 1-100	**74.2%**
Unit 101-on	**90.1%**

Development vs Production

Development vs Production

- **S-curve theory tells us improvement curves during development phase should be relatively flat**
  - **High number of engineering changes**
  - **Late parts due to late engineering release**
  - **Tooling that requires rework**
  - **Engineering errors**
  - **Planned manufacturing processes and part flows don't always work on the shop floor**

- **Learning curve literature tends to gloss this over**
  - **Data from development units is excluded**
  - **Data limitations (lot data vs unit data) preclude analysis of development slopes**

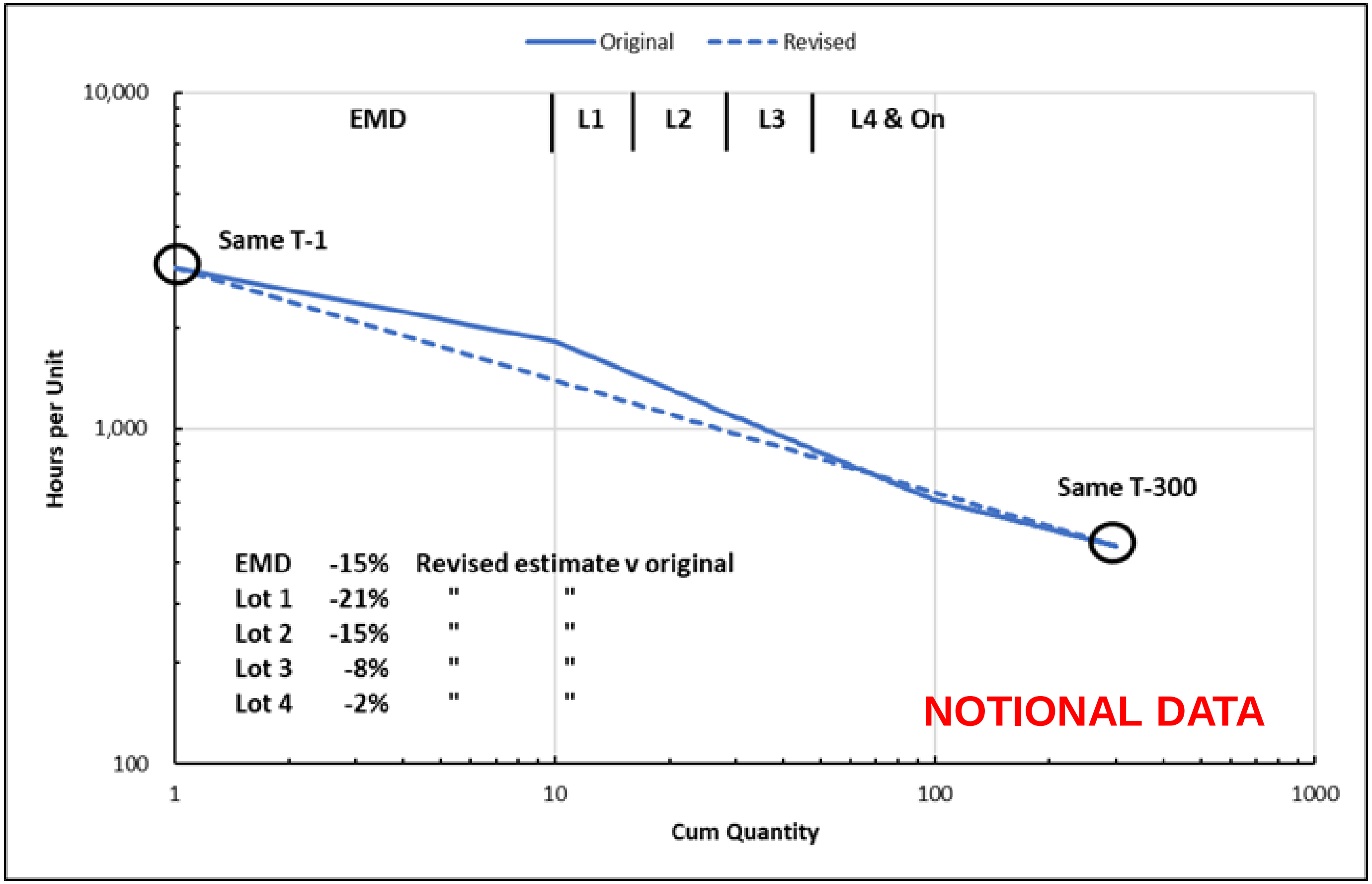
Development vs Production

- **Does it really matter? Take a hypothetical example**
- **Estimator establishes cost of 300-unit program**
  - **Units 1-10: 86% (Development)**
  - **Units 11-100: 72%**
  - **Units 101-on: 82%**

- **Program manager objects:**
  - **"Shouldn't a learning curve be just one line?"**
  - **"A 3-leg slope is too complicated"**
  - **"A flat development curve will look uncompetitive to source selection committee"**
- **Suggests we use the same T-1 and T-300 costs but draw a single line in log-log space between the two**
  - **Recognizes development will be understated, but it's only 10 units**

Development vs Production

- **Unfortunately, more than just the development program is impacted by the program manager's direction…**

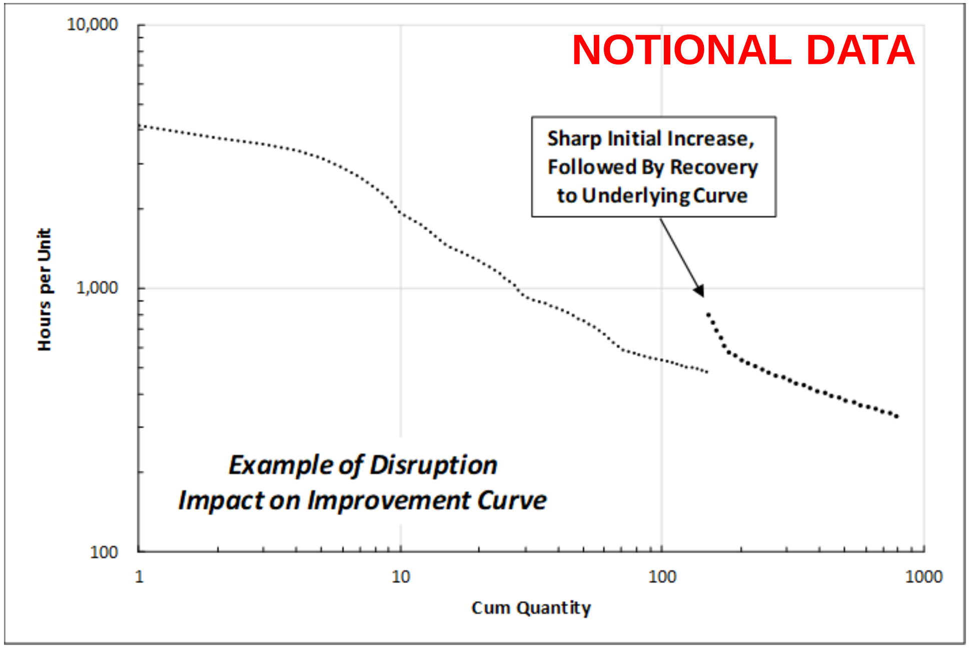


- **Lots 1 & 2 are significantly understated as well – the program is likely to get a bad reputation for overrunning its costs**

Recovery Slopes

Recovery Slopes

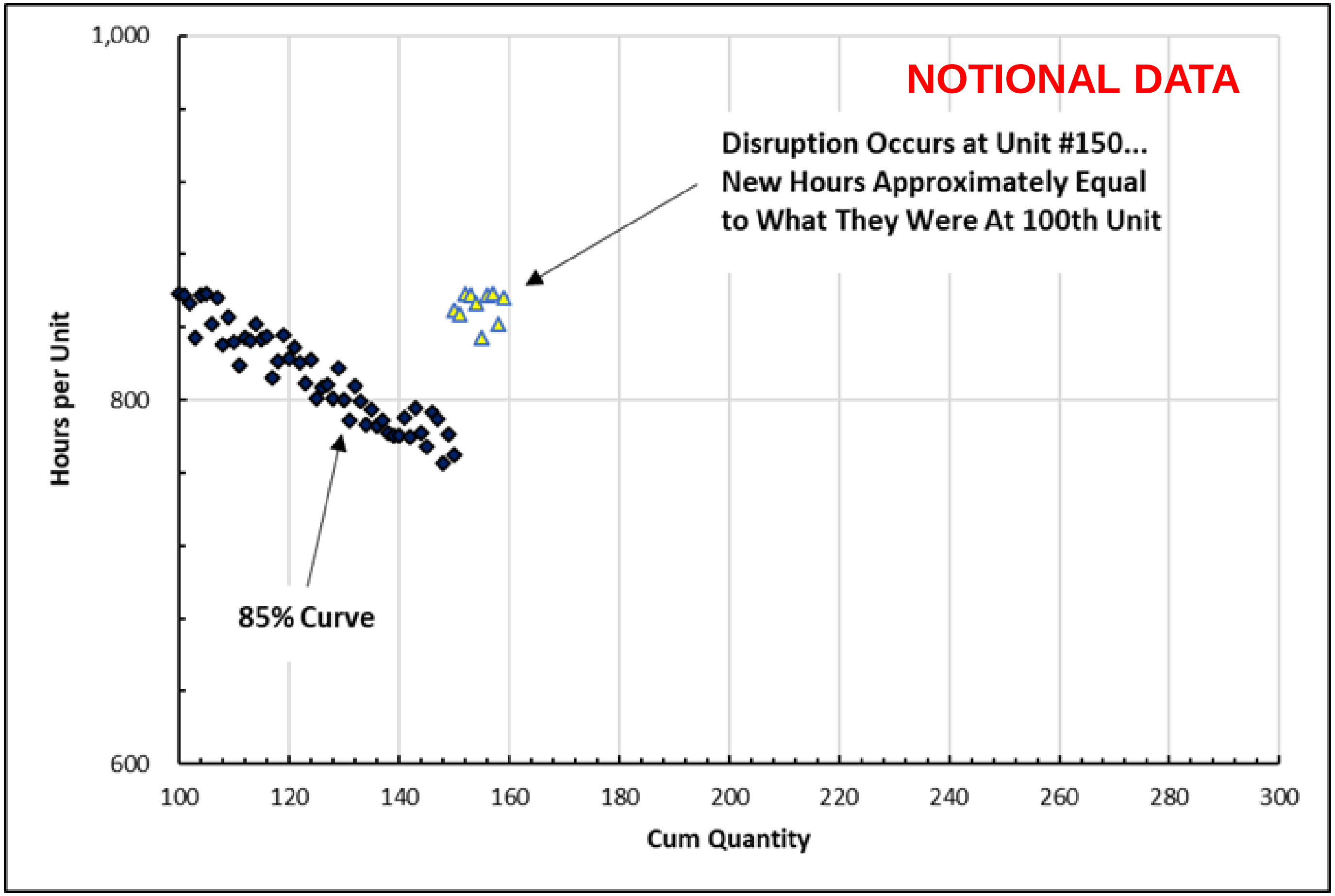
- **One of the most difficult situations for an estimator is a sharp increase in unit cost which is expected to be mitigated over time**
  - **Major engineering changes**
  - **Production break**
  - **Work transfer between sites**
  - **Production issues, i.e., critical load part shortage which creates significant behind schedule or out of station costs**



- **Typically see a sharp increase, followed by eventual recovery to the underlying curve**

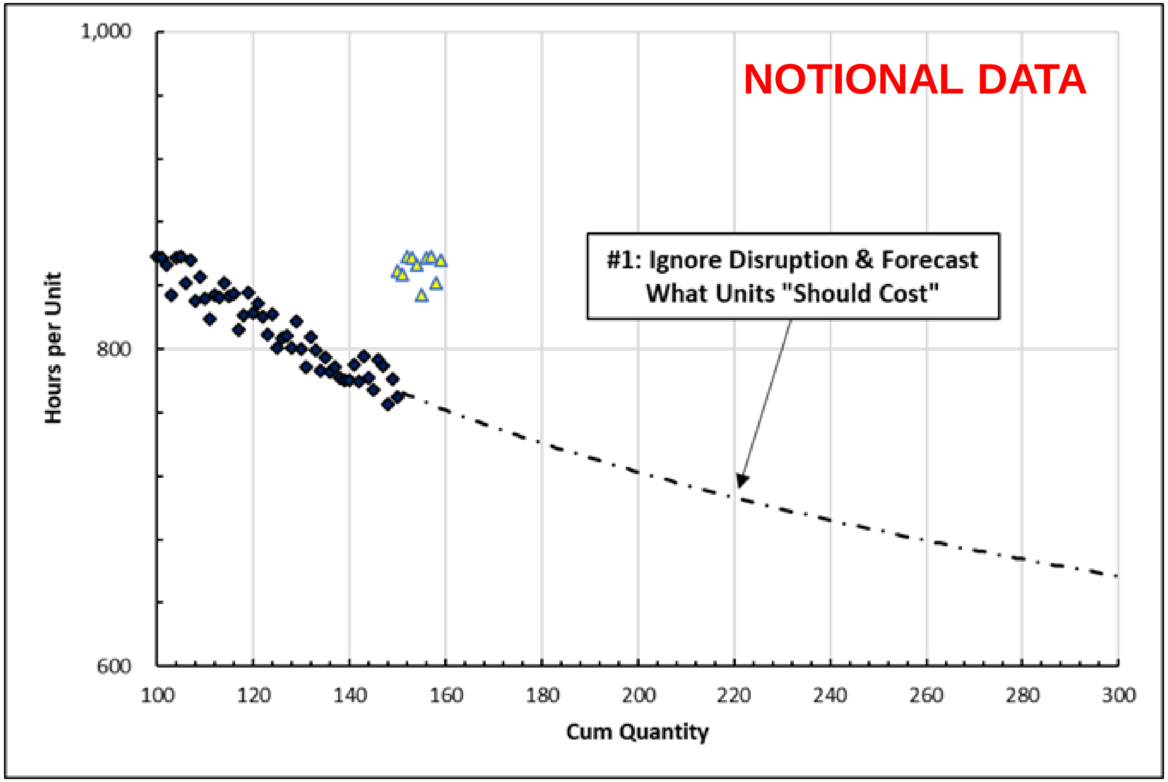
Recovery Slopes - Example

- *Ex ante* we do not know how & when this recovery will occur
- Take a hypothetical example:



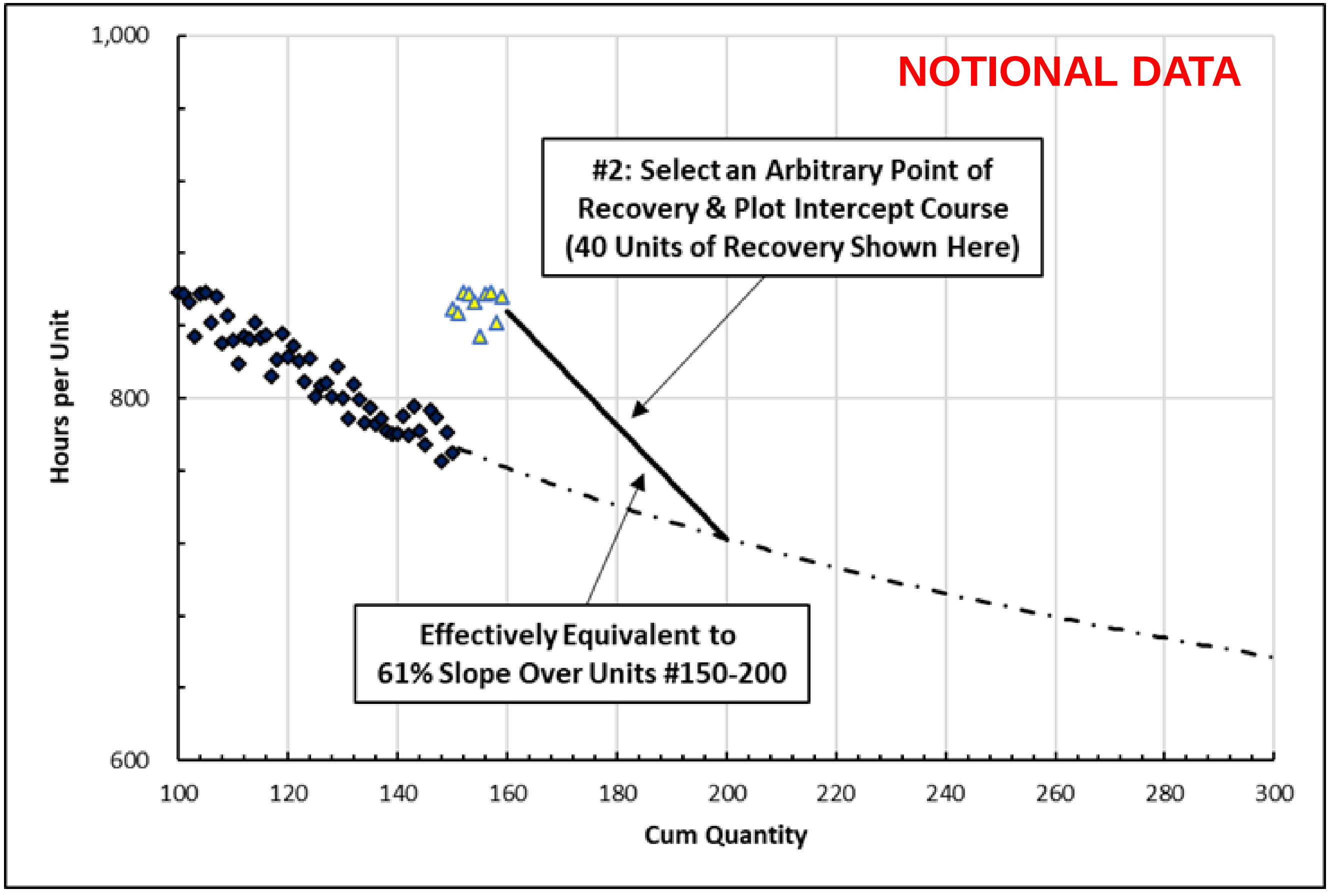
Recovery Slopes – Option #1

- **Option 1: Ignore the disruption & project as if it never happened**
- **Often rationalized on “should cost” grounds**
- **Never justified – the shop floor cannot deal with world as we *wish* it was, but must deal with it as it truly is**



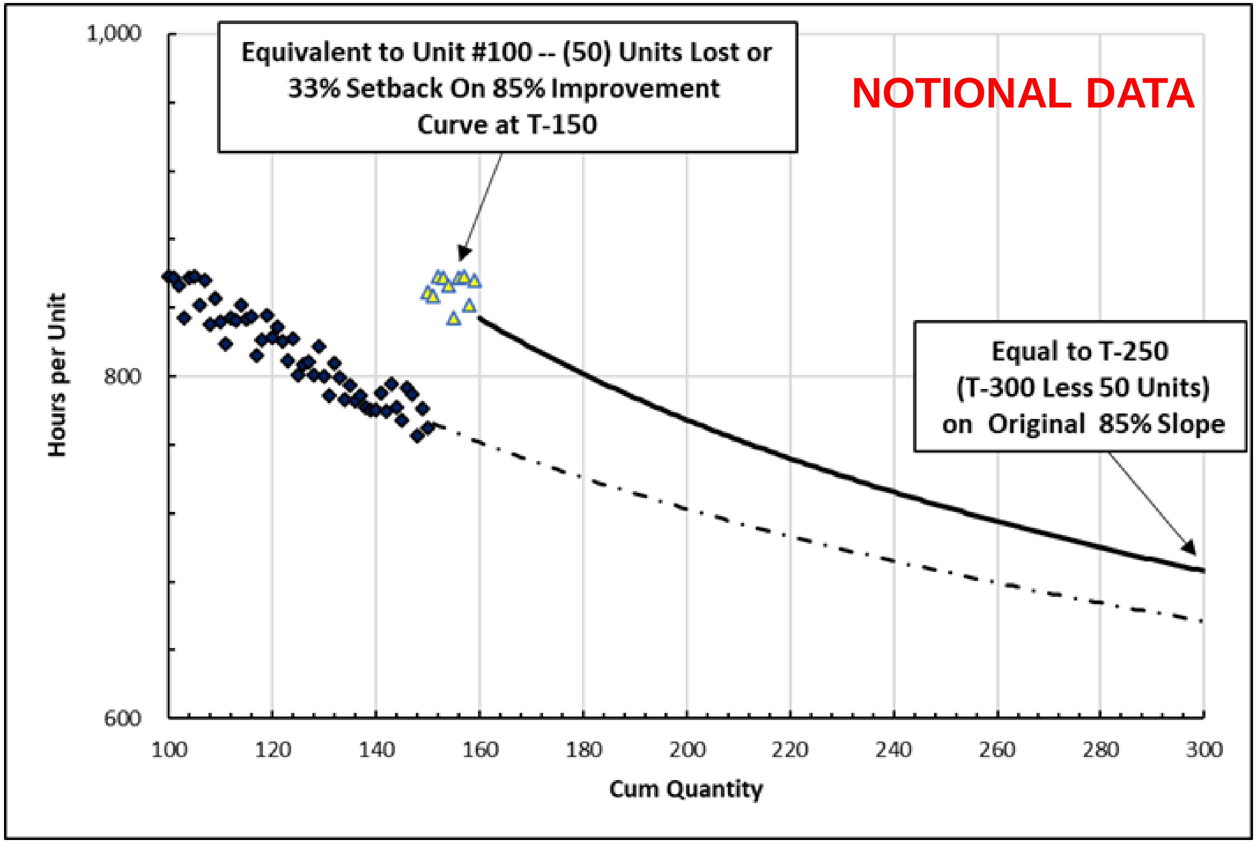
Recovery Slopes – Option #2

- Option 2: Select a point of recovery & plot intercept course
- Point of recovery is almost an arbitrary selection
- Often leads to unrealistically steep slopes that are not achieved



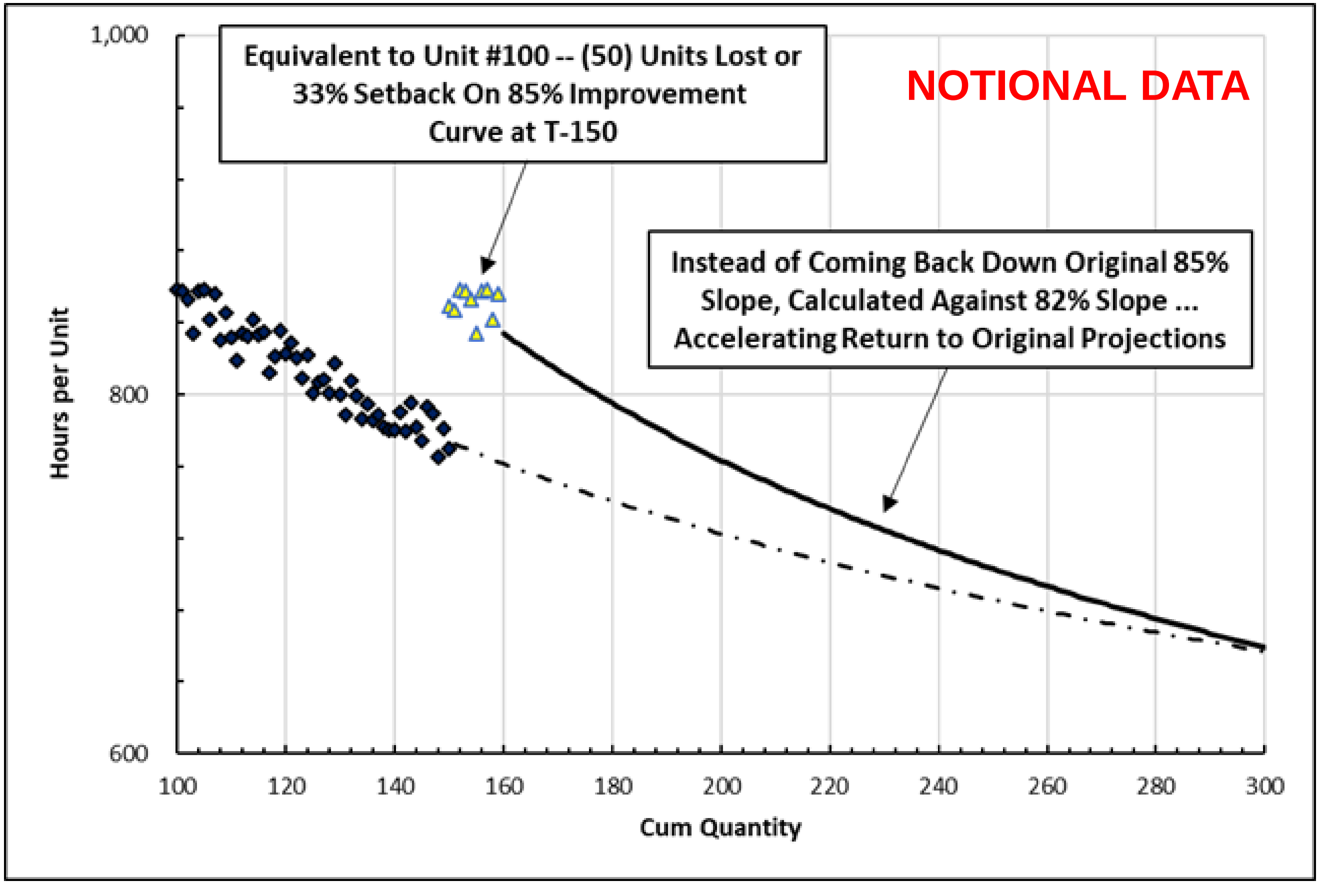
Recovery Slopes – Option #3

- **Option 3: Apply setback on the learning curve using the original slope**
- **Will produce the most conservative answer**



Recovery Slopes – Option #4

- Option: Apply setback on learning curve using an accelerated slope
- Riskier approach: How much acceleration should be applied? Might wind up with an answer that is unexecutable



Recovery Slopes – Observations

- **Analysts sometimes resist setback approach if we are not dealing with a clear-cut change in personnel, i.e., production break**

- **Recall Anderlohr's 5 elements of learning**
  - **Operator learning** ← ***Typically constitutes no more than 20% of total cost improvement***
  - **Supervisor learning**
  - **Tooling**
  - **Continuity of production**
  - **Manufacturing methods**

Production disruptions such as late parts or engineering changes can be successfully modeled by setback methods

- **Murphy's Law can destroy the best-laid plans of production managers – don't plan on perfection but leave some margin of safety**

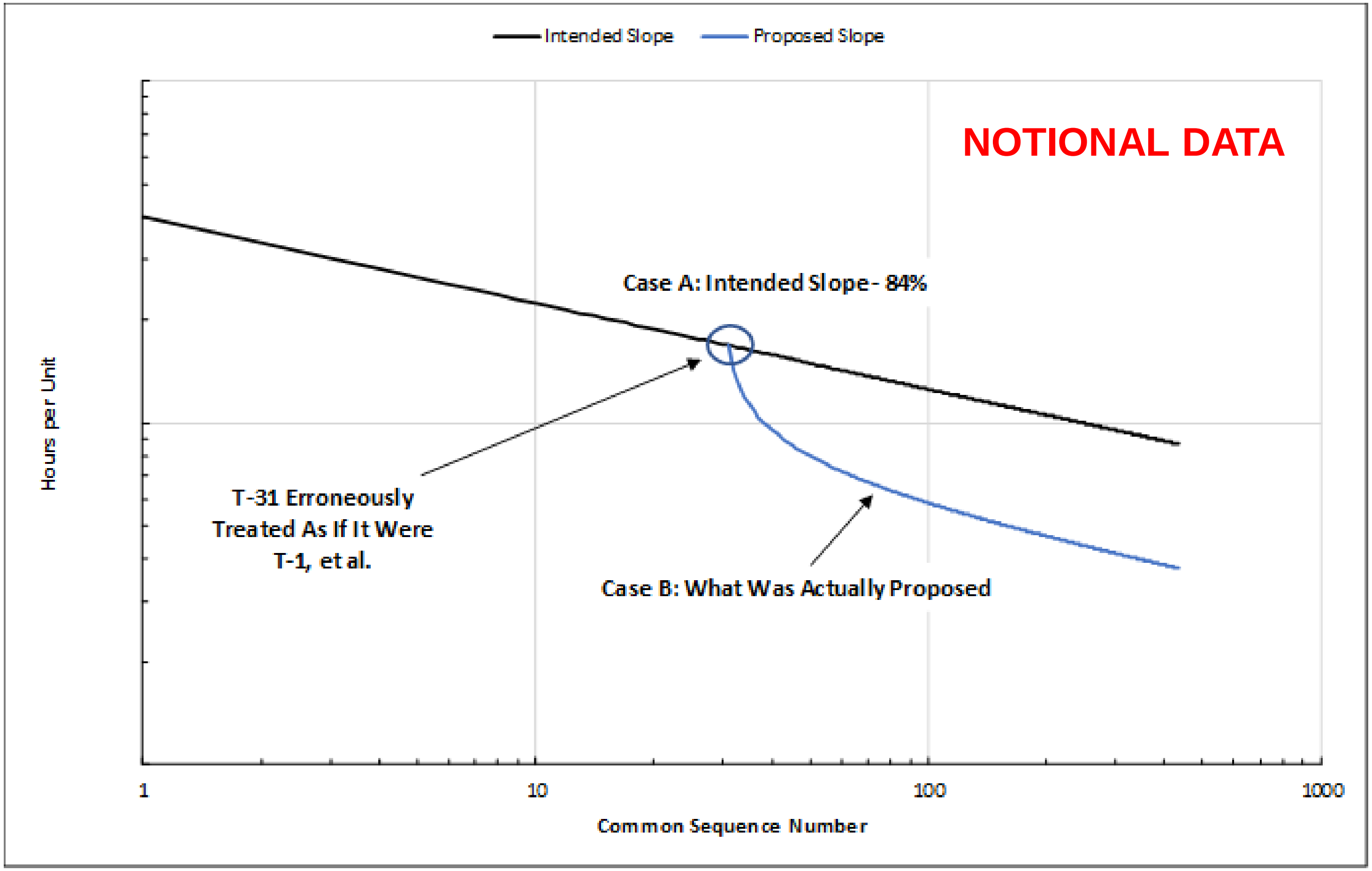
Always Consult Shop Floor Management or SMEs To Insure Your Recovery Is Actually Achievable

First Units

When Is First Unit a First Unit?

- A small pylon requires subassembly work
  - For first 30 units, Special Projects group produced it on 84% learning curve
  - At Unit 31, task transferred from Special Projects to regular Production department, who will produce next 400 units
- Analyst proposed 1st Production unit would be produced at same hours per unit as the last Special Projects unit
  - But for learning curve purposes, he treated it as Unit 1 on 84% curve…not as Unit 31
- Consequences are dramatic: the 16% cost reduction that occurs every time the number of units double has been restarted…*not* the estimator's intention

When Is First Unit a First Unit?



Always Graph Your Results – This Error Would Have Been Caught Had the Analyst Done So

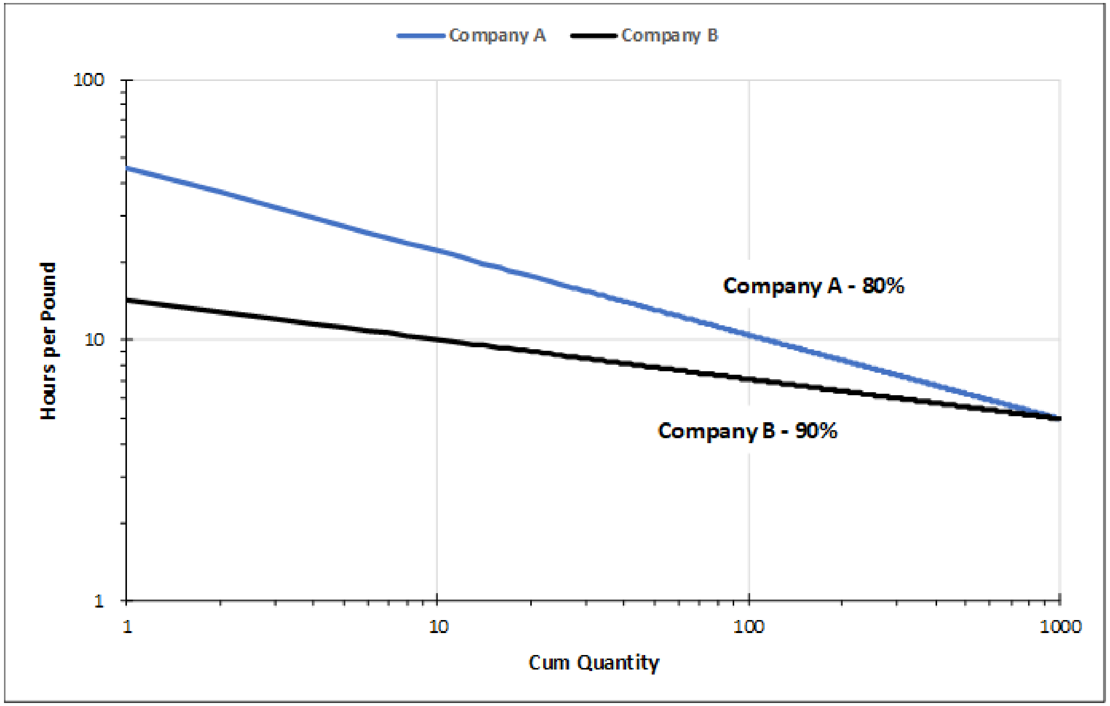
Production Efficiency

Production Efficiency

- Frequently asserted that a flat learning curve is proof of manufacturing inefficiency – and that steep learning curves prove how efficient a manufacturing operation is
- In fact, the slope by itself does not prove if a factory is efficient or inefficient
- Hypothetical example
  - Company A assembles widgets on a 80% slope over 1,000 units
  - Company B build similar but not identical product with a 90% learning curve over the same range
  - There is no transfer of manufacturing knowledge or personnel between the two companies
  - Which is more efficient?

Production Efficiency

- **Have to ask <u>why</u> Company A has a steep curve. It's possible it has so for all the wrong reasons**
  - **High T-1 value driven by late engineering release, inadequate tooling, late material, oversizing of shop floor crews to recover schedule**



- **Company B may have a relatively flat slope for all the right reasons**
  - **Low T-1 accomplished by on-time engineering release, high quality tools, good supply chain performance and efficient crew sizing**

Production Efficiency

- A steep curve can demonstrate strong dedication to cost reduction – or it can indicate the need to recover from poor performance & mismanagement
  - "The more room there is for improvement, the more improvement there is to be expected." (Fowlkes, 1963)

- We cannot determine which is the case just by calculating a learning curve slope – we have to go down another layer and ask why

Conclusion

- **Improvement curves are essential part of cost estimator's toolkit**
- **However, they are easy to misuse – and not know that they are being misused**
- **Reviewed 5 traps analysts can fall into:**
  - **Straight-line projection**
  - **Failure to account for differences in development versus production**
  - **Dangers of recovery slopes**
  - **Carelessness about designating the first unit**
  - **Using learning curve slopes alone to measure production line efficiency**

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