Do Production Rates Really Matter?

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Introduction

- Frequently asserted that higher production rates decrease unit production costs, and vice versa
- Consistent with economic theory
  - Economies of scale suggest average unit costs decrease as production volume increases
- Many analysts include production rate factors in their cost models
- But this conclusion is not universally held – other analysts dismiss the role of production rates or deem their influence statistically insignificant
- Do production rates really matter?

Improvement Curve Formulas

- **Traditional learning is defined as:**

$$Y = MX_1^B$$

Y is labor hours per unit,
M is the theoretical first unit cost,
X_1 is cumulative quantity produced to date
B is the coefficient of learning

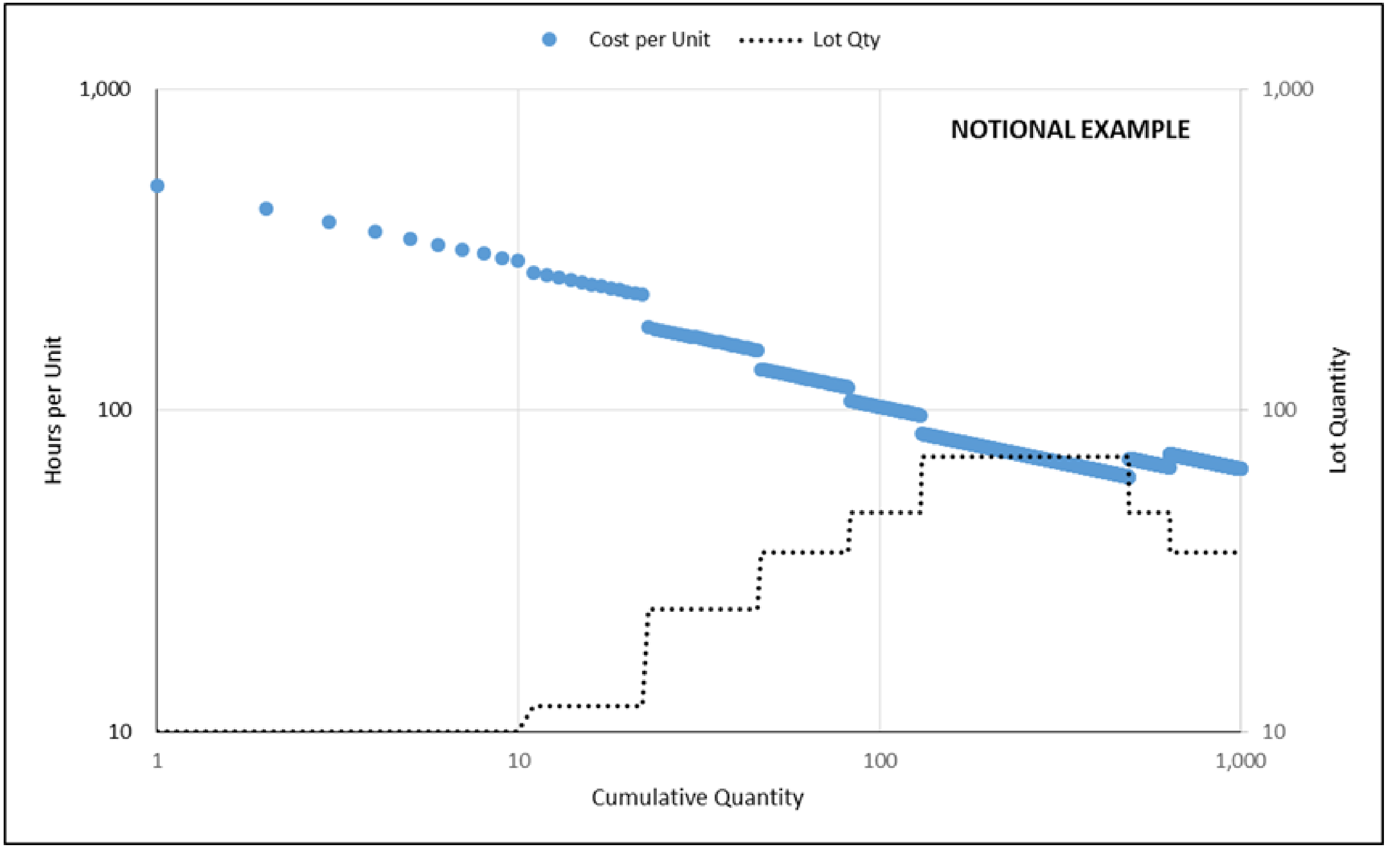
- **Rate augmentation models commonly add a rate variable:**

$$Y = MX_1^B X_2^C$$

X_2 is production rate (usually lot size)
C is the coefficient of rate

Production Rate & Learning

- **Given variation in production rates over time, the improvement curve breaks into segments**



Bemis Study

- **One of the most commonly cited studies is Bemis (1981, 1983):**

	Individual Regressions				Multiple Regression		
	Quantity/Cost		Rate/Cost			Quantity	Rate
System	R^2	Slope	R^2	Slope	R^2	Slope	Slope
Aircraft A	0.949	72.1%	0.543	71.4%	0.974	73.1%	97.5%
Aircraft B	0.924	87.7%	0.852	78.6%	0.948	77.2%	**
Aircraft C	0.876	76.0%	0.918	68.5%	0.995	87.3%	79.5%
Aircraft D	0.498	76.9%	0.769	61.6%	0.923	88.2%	68.0%
Aircraft E	0.984	67.8%	0.992	58.7%	0.997	90.5%	67.2%
Aircraft F	0.461	67.0%	0.945	52.8%	0.994	86.6%	57.3%
Aircraft G	0.988	75.8%	0.972	58.7%	0.999	84.0%	81.4%
Aircraft H	0.929	70.7%	0.664	66.7%	0.971	74.4%	91.4%
Helicopter	0.992	83.1%	0.766	81.9%	0.997	83.8%	89.3%
Jet Engine A	0.943	72.6%	0.425	74.6%	0.984	75.0%	92.0%
Jet Engine B	0.941	69.8%	0.228	76.3%	0.988	71.4%	89.5%
Missile A	0.949	66.0%	0.856	52.5%	0.974	65.1%	**
Missile B	0.724	85.4%	0.214	84.2%	0.873	82.3%	**
Missile G&C	0.468	*	0.672	89.4%	0.981	**	90.7%
Missile G&C	0.672	60.0%	0.980	62.8%	0.996	91.9%	59.4%
Ordnance Item A	0.869	86.6%	0.387	93.2%	0.964	88.1%	97.0%
Ordnance Item B	0.945	76.6%	0.346	*	0.978	97.5%	**
Radar Set A	0.585	87.7%	0.814	86.0%	0.990	93.1%	88.8%
Radar Set B	0.615	94.7%	0.757	88.8%	0.890	98.9%	91.6%
Tracked Vehicle	0.490	*	0.752	88.7%	0.963	**	90.7%
Mean	0.790	76.5%	0.693	73.4%	0.969	83.8%	83.2%

* Positive Quantity/Cost or Rate/Cost Slope

** Addition of Rate Variable Changed Sign to Positive in Multiple Regression

But there are issues….

Rate slope greater than 100%

C ty & ra des better fit to data than a standalone cum qu rve

Cum qty slope greater than 100%

Very wide variation in rate slopes ... from 57% to 98%

In 6 of the 20 cases, the rate or quantity is greater than 100%

Cox & Gansler Study

- **Another commonly cited study is Cox & Gansler (1982):**

	Qty	Rate
Sparrow (1st source)	84.6%	98.5%
Sparrow (2nd source)	87.4%	92.3%
Bullpup	82.3%	100.4%
Tow	99.1%	100.7%
Sidewinder	95.5%	81.9%
Mean	89.8%	94.8%

Again, we have rate slopes greater than 100%

Objections to Rate Models

- **Multicollinearity - Cumulative quantity and production rate are often highly correlated**
  - **Coefficient estimates often unreliable and of the wrong sign.**
- **Statistical Insignificance – Production rate variable often not statistically significant at accepted thresholds of 90% or 95%**
- **Measurement Error – Use of lot size to measure production rates frequently criticized**
  - **Using lot sizes of 15 & 20 aircraft may be misleading if delivery spans are 12 and 16 months respectively (each are delivering at 1.25 aircraft per month)**
- **Theoretical Objections – Absent any kind of capacity constraint, logical conclusion of rate model is that the lowest cost solution is for a contractor to produce all the units in the production program in a single production lot – clearly an impossible event**

Why Might We Expect Rate To Matter

- **Engineering costs are not related to quantity**
- **Higher production rates require more tooling**
- **Setup hours are amortized over larger order sizes as production rates increase**
- **New workers affect assembly performance negatively, at least in the short-term**
- **Quantity discounts reduce unit procurement costs**
- **New workers are typically paid less, reducing production labor rates**
- **Additional business volume reduces overhead rates**

Reasons Sometimes Suggested For Rate Effects

Manufacturing – Short Term

- **Critical we separate _short-run_ versus _long-run_ impacts**
- **In short-term, production rate increases or decreases produce _higher_ unit costs**
- **Rate increases require new hires who need introductory period of learning before fully productive**
  - **Many examples of short-term rate impacts in commercial aircraft industry**

Manufacturing – Short Term (cont'd)

- **Boeing 737 & 747 (1997)**
  - **"In early October, overwhelmed by thousands of foul-ups, Boeing temporarily halted production of the 747 as well as the smaller 737….Boeing had to scramble to find people to build its airplanes, hiring 32,000 workers in the last 18 months. Despite what they describe as an aggressive training program, with five weeks of instruction before starting work, Boeing executives conceded that many new workers were still not fully prepared. 'We have incurred the penalty of these people learning' on the job, said Gary R. Scott, the vice president in charge of producing the 737 and 757." (New York Times, 1997)**
- **Boeing 747 (late 1960s)**
  - **"At the time production was starting on the 747, Boeing could not find enough workers in the Seattle area and was forced to recruit intensively. Of the workers hired, less than half developed into normally productive workers. Labor hours per aircraft increased as production rate and cumulative quantity increased, i.e., the learning curve had a positive instead of a negative slope." (RAND, 1974)**
- **Douglas Aircraft (late 1960s)**
  - **DC-8 & DC-9 production**

Manufacturing – Short Term (cont'd)

- Rate decreases require employee layoffs and reassignment of remaining workers – particularly in union shops where 'bumping' rights exist
  - Union agreements limit company's ability to avoid impacts due to abrupt schedule changes
- When production rates decelerate:
  - Personnel reductions are accomplished by "bumping"
    - Each "bump" to new grade involves reorientation to new task assignment
    - 4 to 5 "bumps" often required to accomplish a one man layoff
  - Reduced tempo
  - Repeated breaks for task assignment changes
  - Reduced specialization as remaining personnel must do more
  - Limited utilization of laid-off personnel in the immediate days prior to lay-off

Manufacturing – Long-Term

Production Rates Have Significant Impact

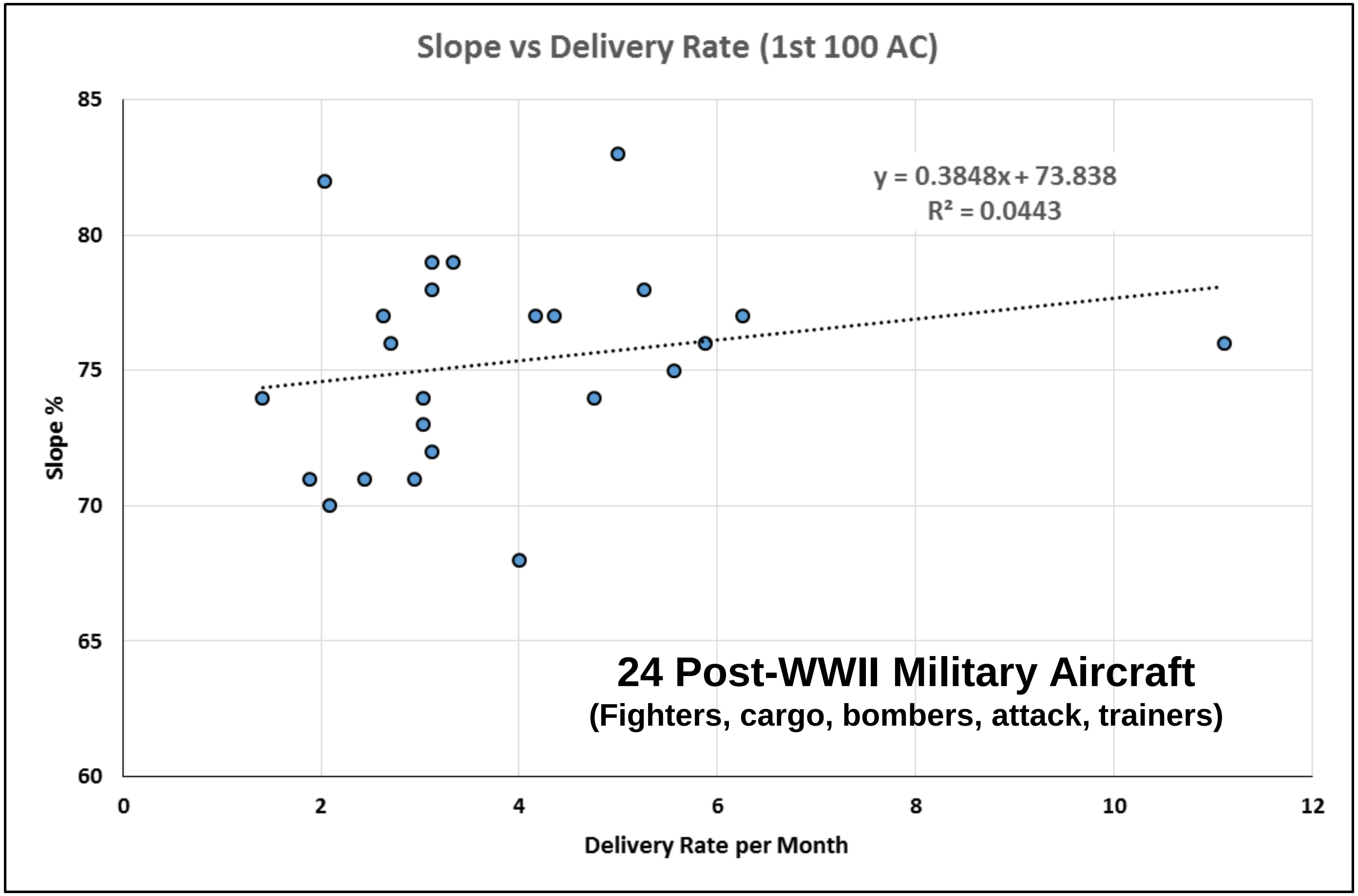
- **Johnson (1969) –** Rocket engines
- **Orisini (1970) –** C-141 aircraft
- **Groemping (1976) –** A-7, F-4, A-4, F-86, F-102, F-8 aircraft
- **Smith (1976) –** F-4, F-102, KC-135 aircraft
- **Congleton (1977) –** T-38/F-5 aircraft

Production Rates Have Insignificant Impact

- **Alchian (1950) –** World War II Aircraft
- **Hirsch (1952) –** Machine tools
- **Asher (1956) –** Post-WWII aircraft
- **Large (1974) –** Post-WWII aircraft, missiles
- **Bourgoine & Collins (1976) –** A-10 aircraft
- **Benkard (2000) –** L-1011 aircraft
- **Younossi (2001) –** F-14, F-15, F-16, F-18, AV-8B aircraft

Manufacturing – Long-Term

- RAND studied improvement curve slope and delivery rate
  - Expectation: Higher production rates = Steeper slopes
  - Reality: Little to no relationship between slope and rate



Support Labor

- Very little published research on impact of production rates on support labor
- Yet support labor is a significant contributor to cost
  - Support is 50-120% of touch labor for recent military aircraft, depending on production phase
- Look at:
  - Tooling
  - Engineering
  - Quality Assurance

Engineering & Tooling Labor

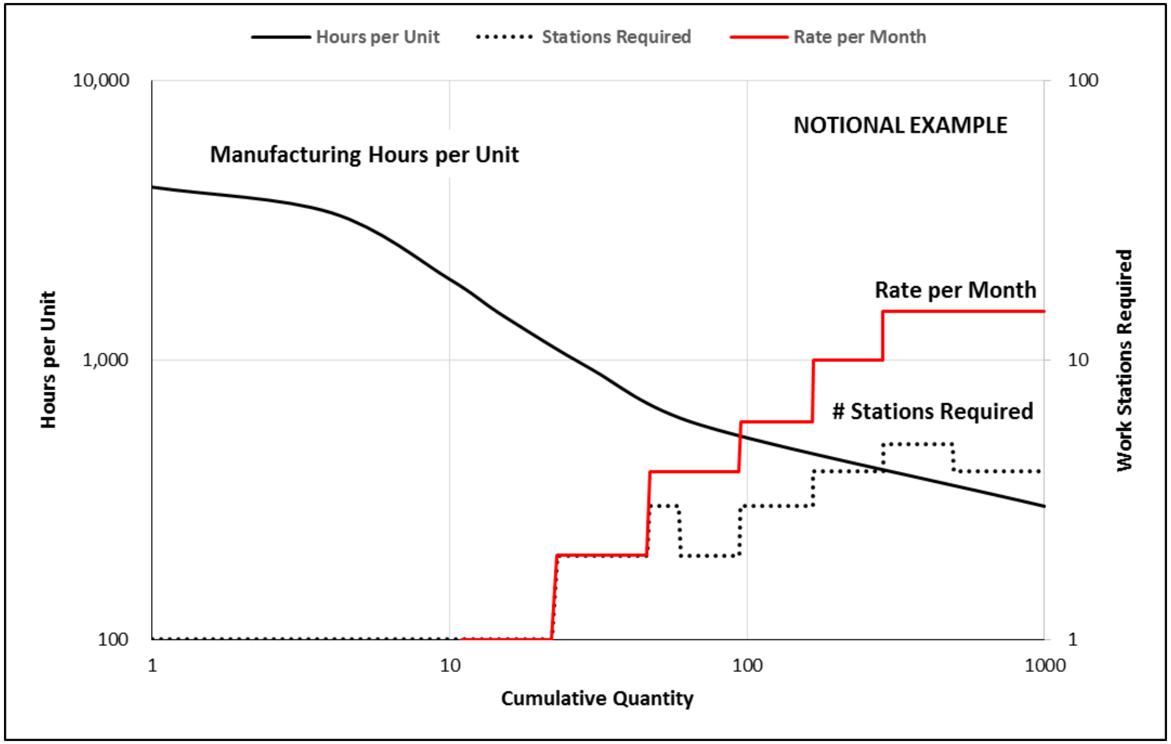
- **Tooling – fabrication & subassembly of major jigs, dies, fixtures, work platforms and test equipment. Also includes manufacturing engineering, manufacturing & tool planning, tool design and NC programming**

- **Engineering – design, analysis, and test of product. Includes engineering disciplines such as stress, aerodynamics, weight, reliability & maintainability, low observables, mission & vehicle systems, EEE, systems engineering, flight test.**

Non-Recurring Tooling

- **Non-recurring tooling is creation of initial set of tools, tool designs and planning + duplicate tooling for increased production rate**

$$\frac{[Hours\ per\ Unit\ \div (Crewload\ x\ Hours\ per\ Day\ x\ Shifts\ per\ Day)]}{Days\ Worked\ in\ Month\ \div Production\ Rate\ per\ Month} = No.\,of\ Stations\ Required$$



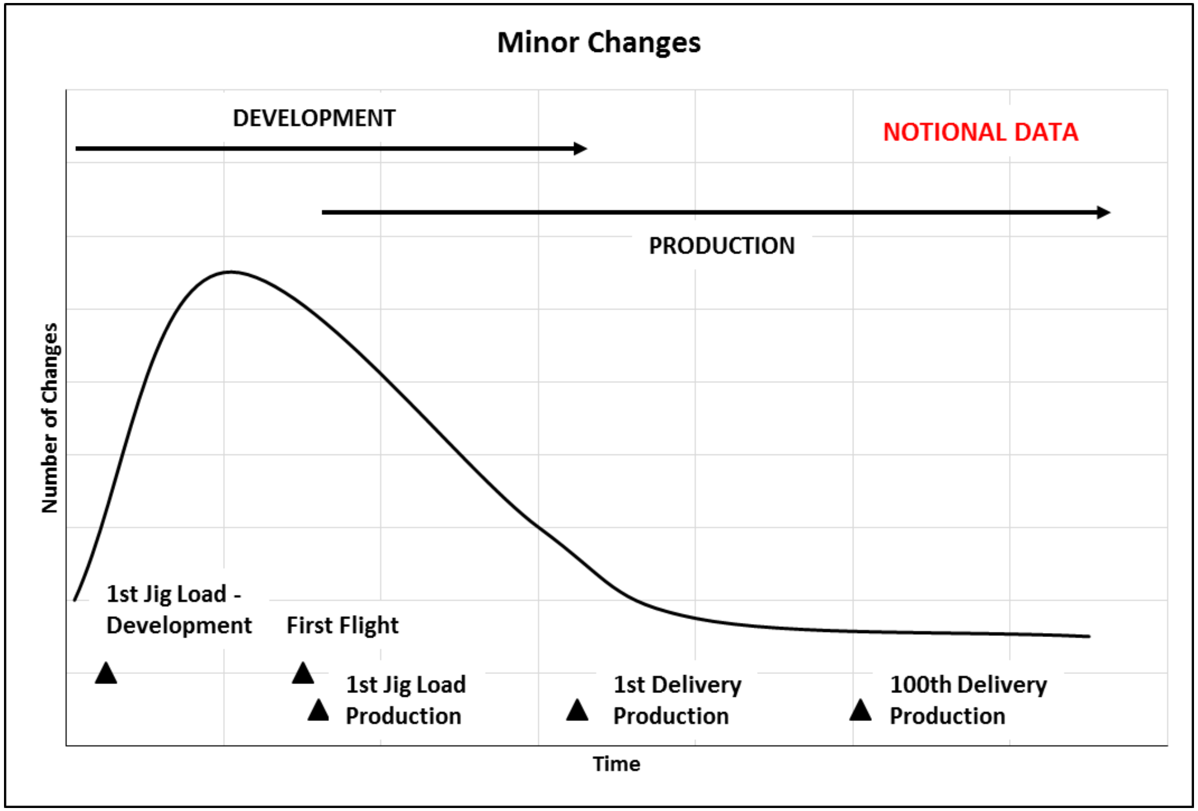
- **Expect relationship between duplicate tooling and production rate**
  - **Not one-to-one, but increased rates create step functions when requirements exceed existing tool capacity**

Sustaining Engineering & Tooling

- Sustaining engineering & tooling share similar characteristics
- Covers variety of tasks
  - Material Review Board (MRB) disposition
  - Investigation of quality non-conformances
  - Incorporation of minor (Class II) engineering changes
  - Floor liaison / investigation of “squawks”
  - Maintenance of drawings, tools, designs and planning
  - Configuration management (Engineering)
- Sustaining impacts can be driven by cumulative quantity or production rate

Sustaining Engineering & Tooling

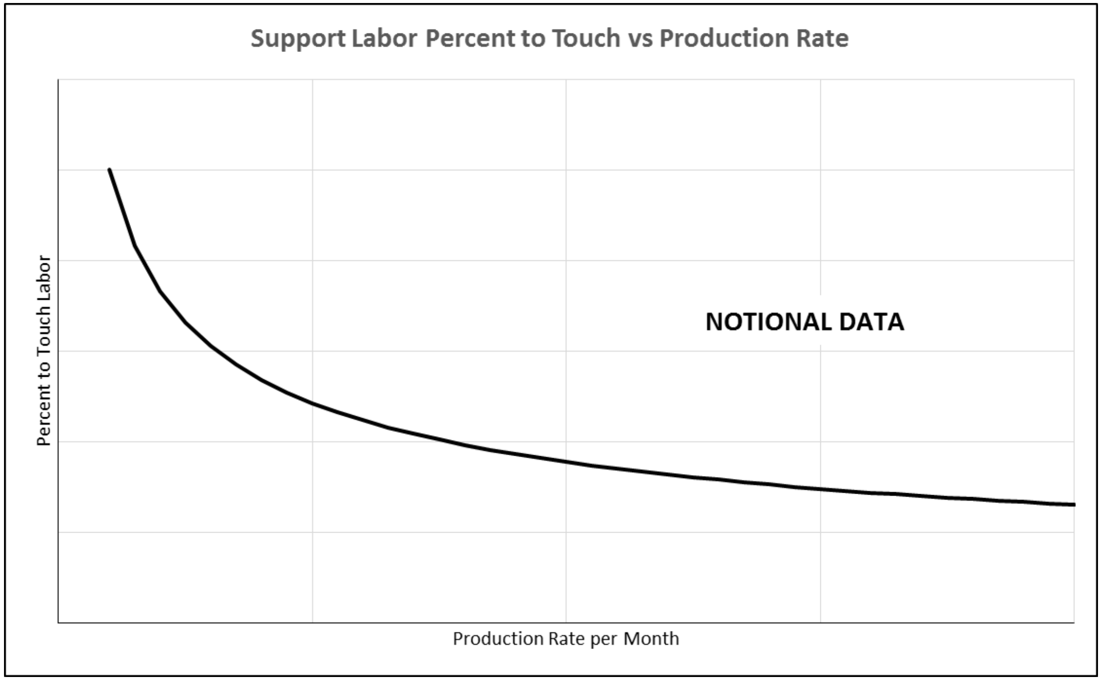
- For example, cost impact of minor changes decreases across build
- As parts are built, problems are found in initial designs & tools



- Change traffic rises rapidly during initial subassembly & assembly
- Corrections & modifications are made incrementally
- As “low hanging fruit” is picked, volume of changes begins to taper off over time

Sustaining Engineering & Tooling

- It is sometimes assumed sustaining manpower is fixed & does not vary regardless of production rates
- Tasks such as factory liaison & quality non-conformances require more staffing at higher rates, but there is also a fixed element
  - Particularly visible at very low rates, when minimum staffing considerations come into play



- Support labor ratios are typically inverse to production rate
- At low rates, minimum staffing considerations drive high support labor ratios
- At high rates, fixed costs are distributed across more units

Tooling

- **What do the studies show about influence of production rates on tooling costs?**

- **Large (1974, Post WW-II Data): Relationship between cum tooling hours and production rates was not statistically significant**
  - **RAND was skeptical of result, since hours included non-recurring (duplicate) tooling**

- **Younossi (2001, MACDAR): Statistically significant relationship between tooling hours per unit and production rate**
  - **Learning slope: 77% Rate slope: 75%**

Engineering

- **What about engineering?**
- **Large (1974, Post WW-II Data): Statistically significant relationship between cum engineering hours and production rates**
- **Younossi (2001, MACDAR): Relationship between engineering hours per unit and production rate was not statistically significant**
  - **Learning slope: 71% Rate slope: 88%**

In my experience, sustaining tooling & engineering are both impacted by production rate – but published research is ambiguous

Quality Assurance

- **Quality Assurance – inspection of manufactured items; determination of quality specifications, methods and processes of inspection; maintenance of quality records**

- **Found only one study which dealt with quality**

- **Younossi (2001, MACDAR): Relationship between quality hours per unit and production rate was not statistically significant**
  - **Learning slope: 85%   Rate slope: 95%**

Overhead / Indirect Costs

- **53% of contract cost in defense industry is overhead / indirect cost**
  - **By contrast, less than 30% of product cost is touch labor or direct material. (Saha, 2002)**
- **Typically composed of:**
  - **<u>Fixed costs</u>: Depreciation, taxes, insurance, utilities, rents and professional services**
  - **<u>Semi-fixed costs</u>: Data processing, allocation of corporate expenses, IRAD, B&P**
  - **<u>Variable costs</u>: Indirect labor, machine maintenance, operating supplies, training expenses, and travel**

Fixed & semi-fixed costs are significant

Overhead / Indirect Costs

Gilbride, 1983

(15 Aircraft Companies, 1975-1986, From DD 1921-3 Information)

- **10 percent increase in business base drove:**
  - **a 3.5 percent decrease in manufacturing overhead rates,**
  - **1.7 percent decrease in engineering overhead rates,**
  - **5.8 percent decrease in material overhead rates, and**
  - **4.6 percent decrease in G&A rates.**
- **10 percent decrease in business base drove:**
  - **a 4.9 percent increase in manufacturing overhead rates,**
  - **6.8 percent increase in engineering overhead rates,**
  - **8.4 percent increase in material overhead rates, and**
  - **10.5 percent increase in G&A rates.**

Large, 1974

(5 Aerospace Companies, 1960-1972)

- **4 percent increase in direct labor caused a 1 percent decrease in the overhead rate, and vice versa**

Production rate impacts volume of business, and business volume has substantial impact on overhead rates

Impact of Production Rate on Unit Cost

Functional Area	Strong	Moderate	Weak	None or Uncertain
Manufacturing (Short-Term)	Increase in hours for rate changes, positive or negative			
Manufacturing (Long-Term)			Inversely correlated	
Tooling (Rate)	Positively correlated			
Tooling (Sustaining)		Inversely correlated		
Engineering (Non-Recurring)				None apparent
Engineering (Sustaining)		Inversely correlated		
Quality Assurance				Insufficient evidence
Manufacturing Materials			Inversely correlated	
Overhead / Indirect	Inversely correlated			
Total Weapon System		Inversely correlated		

Inversely correlated: Increased rate, lower unit cost

Positively correlated: Increased rate, higher cost

Areas For Future Research

- **Astute listener has noticed most of these studies occurred during 1960-1990 timeframe…limited research in recent years**
- **Dominated by military aircraft, limited study of other hardware**
- **Most of the research has focused on manufacturing labor hours, and not support labor or overheads**
- **Very little published research on impact of production rates on improvement curves outside defense industry**

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