Learning Rate Sensitivity Model

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Introduction

Learning in Space System Cost Estimating

- Learning curves are frequently used to model reduction in per unit cost associated with a manufacturing production run
  - *Usually, humans get better at doing things thus later units cost less than early ones*
- Historically, space system production runs have been small (1 to 4 units)
  - *Using an assumed learning rate assumption has produced reliable results*
  - *Partially, learning rate assumed has not been a very large driver in overall cost*
- Future, space is changing and many organizations are proposing or interested in unprecedentedly large production runs (100's to 1000's of units)
  - *Learning rate can be the most significant driver to overall cost*
- Large production cost estimates are highly sensitive to learning rate assumed
  - *With large numbers of spacecraft, it is necessary to test assumptions about learning rates versus cost estimates*

As space moves to large production runs, learning rate assumptions become critical and need to be re-visited

Introduction

Learning in Space System Cost Estimating

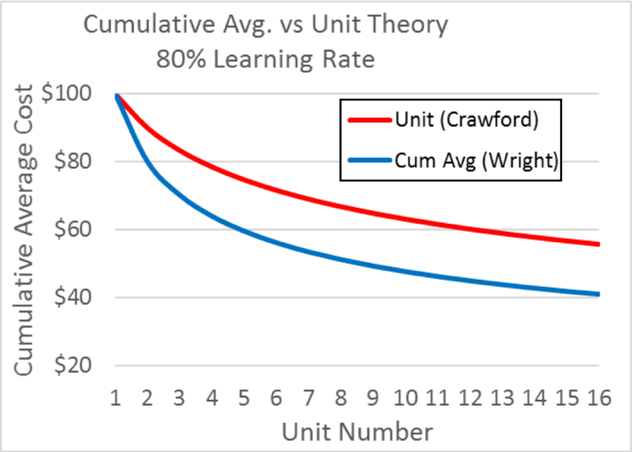
- The Aerospace Corporation has developed a methodology to test assumptions about learning rates vis a vis proposed cost estimates

- Suppose a spacecraft provider makes claims about the learning rate associated with a cost estimate for a high production rate acquisition
  - *We have developed a methodology to provide a data-driven assessment of whether this learning rate/cost combination is feasible, or even likely*
  - *The sensitivity model further describes the learning rate that would need to be achieved to meet a proposed cost estimate, and how likely that learning rate is to being achieved based on the past history of other high rate production processes*

- While this process was developed for a space application, it is equally applicable to other manufacturing processes with large numbers of units

Learning Curves Review

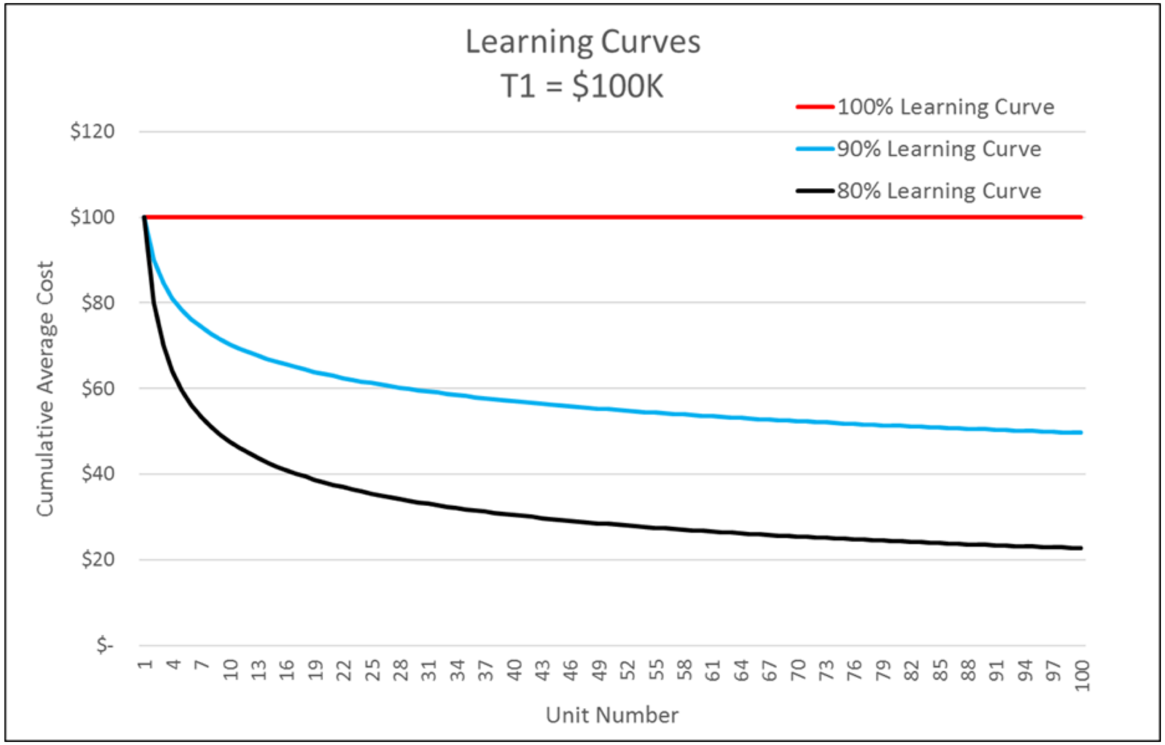
- Learning curves enjoy wide use as a tool to estimate recurring costs in a production process
  - *In general, as production quantity increases, manufacturing cost decreases in a predictable manner*
- Two models in most widespread use:
  - *Cumulative Average Theory (Wright) – Original model from 1936*
    - Every time production quantity is doubled, the average cost required to build a group of n units decreases by a constant percentage
  - *Single Unit Theory (Crawford)*
    - Every time production quantity is doubled, the cost required to build that last single n^{th} unit decreases by a constant percentage
- Both approaches are valid but should not be mixed
  - *For a given "% Learning Rate," cumulative average represents faster learning than unit theory*



For this study, using cumulative average (Wright) model

Learning Curves Review (Continued)

- Failure to model learning, when it exists, is equivalent to assuming a 100% learning curve (i.e., no learning)
  - *Each unit costs the same as the first one built*
  - *This results in cost estimates that are larger than reality*



If neglect to include learning, then cost estimates are unrealistically high

Problem Description

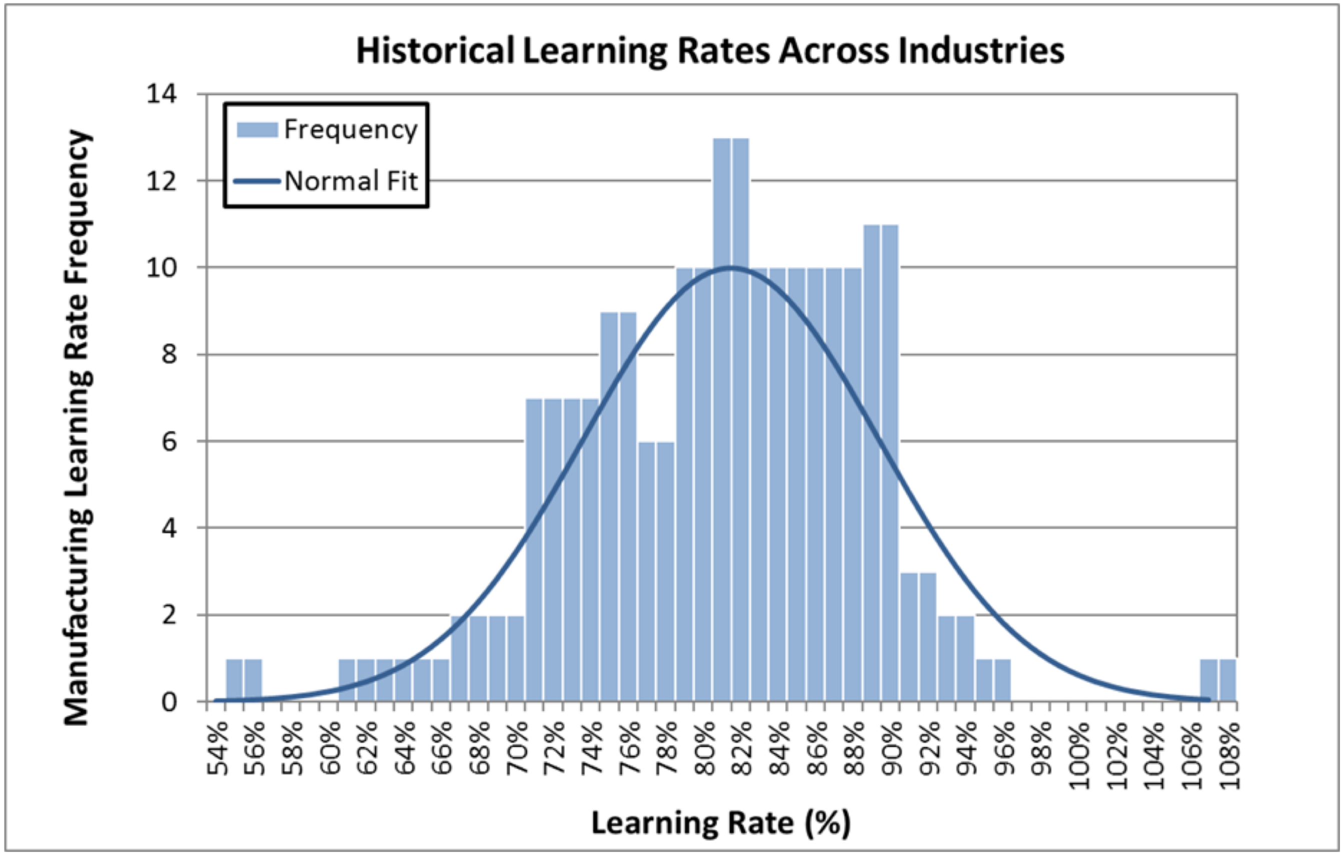
- What is a realistic learning rate for high production space systems?
  - *There is little to no historical, empirical data available in space industry*

- Look to empirical data from other industries
  - *Ideally, complex manufacturing processes which produce 100's to 1000's of units*
  - *Examples: aircraft, ships, trucks, power plants, petroleum products, etc.*
  - *Leverage work by Linda Argote and Dennis Epple who estimated the learning rate of a broad collection of manufacturing programs*

- We provide a mechanism to evaluate realism learning rate/cost combinations
  - *Given an estimate first unit cost for the hardware in question*
  - *We determine the learning rate needed to achieve a total proposed cost*
  - *Compare derived learning rate to a collection of learning rates achieved by over 100 projects across a variety of industries to assess difficulty in achieving the derived learning rate*
  - *Perform sensitivity analysis of total cost versus learning rate*

Historical Learning Rates in Manufacturing

- In their paper, "Learning Curves in Manufacturing[1]," Linda Argote and Dennis Epple collected data on observed learning rates from more than 100 different manufacturing processes across a wide range of industries
  - *The following chart is a histogram representing the learning rate frequency derived from Argote and Epple's paper*



[1]Linda Argote and Dennis Epple, "Learning Curves in Manufacturing," *Science*, vol. 247, no. 4945, 1990, pp. 920-924.

The Learning Rate Sensitivity Model

- The learning rate plays a major role as a cost driver
  - *But it is one of the least known, unpredictable aspects of the cost estimate*
  - *In their paper, "Historical Cost Improvement Curves for Selected Satellites[2]," Peter Meisl and Lana Morales proposed broad-based cumulative average theory learning rates of 95% for 1-10 units, 90% for 11-50 units, and 85% for 50 or more units, as well as specific learning rates for individual subsystems*
  - *While useful for estimating cost, setting learning rates to some static value ignores a major driver of cost risk due to the volatility of learning rates observed*
- The Learning Rate Sensitivity Model is constructed with the goal of helping decision makers understand the sensitivity of a cost estimate to the assumed learning rate
- Has been implemented in the Concept Design Center (CDC) cost model
- Developed using Visual Basic for Applications
  - *Iteratively computes cost estimates using learning rates that span the range of those found in different industries, from 54% to 108%*
  - *Identifies implied learning rate of the original cost estimate*
  - *Computes the cumulative probability of achieving such a learning rate based on industry data*
  - *Provides numerical and graphic representation of cost estimates that would arise assuming different learning rates*

[2]Peter Meisl and Lana Morales, "Historical Cost Improvement Curves for Selected Satellites: Final Report," Management Consulting and Research, Inc., TR-9338/029-1, 1994.

Example (1 of 5)

- Consider the following example CDC cost estimate of a commercial satellite program containing a large number of units with a high production rate

Mean Parametric Cost Estimate for the Commercial Class D Program					
	Sat+Grnd Dev	Sat+Lnch Prod	Total	Sat T1	Sat Ta for 500
Total Cost (FY18$M)	**$216**	**$8,501**	**$8,717**	**$56**	**$13**
Total Cost (FY18$K)	**$216,012**	**$8,501,137**	**$8,717,149**	**$55,826**	**$13,002**
SPACE SEGMENT (FY18$K)	**$216,012**	**$6,177,692**	**$6,393,704**	**$53,048**	**$12,355**
Payloads	**$34,314**	**$3,221,773**	**$3,256,087**	**$27,666**	**$6,444**
Communication System	$34,314	$3,221,773	$3,256,087	$27,666	$6,444
Bus	**$13,901**	**$1,915,873**	**$1,929,775**	**$16,452**	**$3,832**
Propulsion	$505	$133,038	$133,543	$1,142	$266
ADCS	$2,157	$283,243	$285,400	$2,432	$566
TT&C	$1,157	$134,778	$135,935	$1,157	$270
C&DH	$2,445	$284,723	$287,168	$2,445	$569
Thermal	$476	$51,185	$51,661	$440	$102
Power	$3,471	$632,300	$635,771	$5,430	$1,265
Structure	$3,689	$396,606	$400,296	$3,406	$793
Flight Software	**$138,552**		**$138,552**		
Integration, Assembly & Test	**$10,300**	**$438,961**	**$449,261**	**$3,769**	**$878**
Program Level	**$18,945**	**$601,085**	**$620,030**	**$5,162**	**$1,202**
LAUNCH SEGMENT (FY18$K)		**$2,323,445**	**$2,323,445**	**$2,777**	**$647**

- The total cost is estimated at $8,717M (FY18), derived using the Maisel and Morales learning rate assumption guidance
  - *Similarly, could be used to reproduce a developer's cost estimate, enabling sensitivity analysis of the developer's learning curve assumptions*

Example (2 of 5)

- Upon completion, the Learning Rate Sensitivity Model is activated, cycling the cost estimate through all learning rates experienced in industry (54% - 108%) resulting in the following table of cost estimates versus learning rates

Learning Rate Assumption	Mean Total Cost (FY18$M)
54%	$2,285
55%	$2,298
56%	$2,314
57%	$2,331
58%	$2,352
59%	$2,376
60%	$2,404
61%	$2,436
62%	$2,473
63%	$2,516
64%	$2,566
65%	$2,623
66%	$2,689
67%	$2,765
68%	$2,852
69%	$2,952
70%	$3,067
71%	$3,198

Learning Rate Assumption	Mean Total Cost (FY18$M)
72%	$3,347
73%	$3,518
74%	$3,714
75%	$3,936
76%	$4,190
77%	$4,478
78%	$4,806
79%	$5,178
80%	$5,601
81%	$6,080
82%	$6,622
83%	$7,237
84%	$7,932
85%	$8,717
86%	$9,604
87%	$10,605
88%	$11,734
89%	$13,005

Learning Rate Assumption	Mean Total Cost (FY18$M)
90%	$14,437
91%	$16,048
92%	$17,859
93%	$19,893
94%	$22,177
95%	$24,739
96%	$27,610
97%	$30,827
98%	$34,428
99%	$38,456
100%	$42,958
101%	$47,988
102%	$53,601
103%	$59,863
104%	$66,843
105%	$74,619
106%	$83,274
107%	$92,902
108%	$103,605

Example (3 of 5)

- From this table, we can determine what the cost estimate would be for a given cumulative average (Wright) learning rate.,
  - *e.g. an 80% learning curve assumption = a mean cost estimate of $5,601M (FY18).*
- Now suppose that a spacecraft developer were to propose a cost estimate of $3,000M, while asserting that its learning rate is 80%
- This table would suggest that their cost estimate should be closer to $5,601M if their learning rate assumption is 80%
- Also shows that the developer would need to achieve about a 70% learning rate for total production to cost $3,000M

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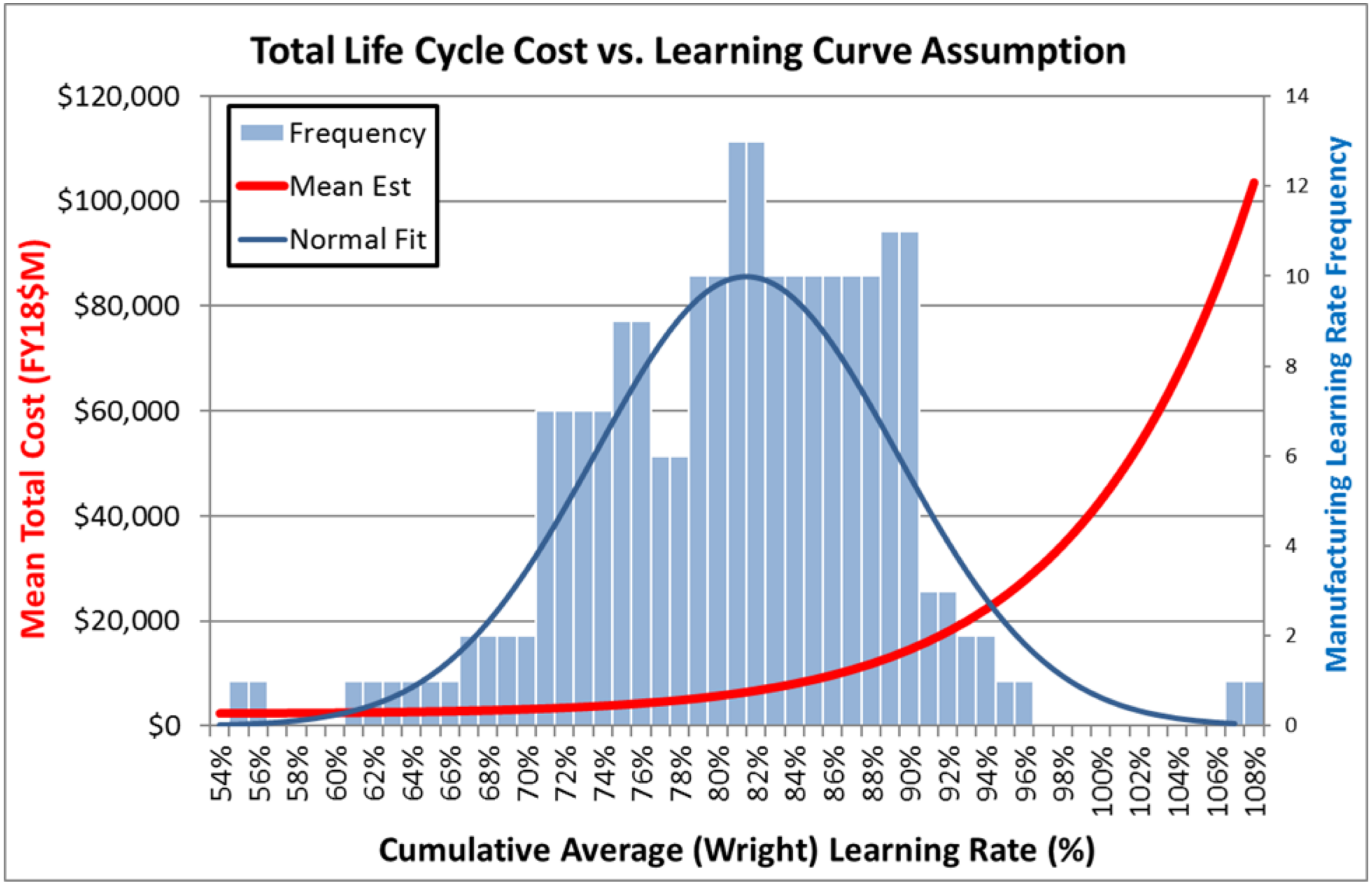
Example (4 of 5)

- Now we overlay the cost estimates versus learning rates with the industry learning rate data
  - *The cost estimate vs. learning rate (red curve) illustrates graphically the sensitivity analysis of the cost estimate as a function of the assumed learning rate*



Example (5 of 5)

- Suppose now that the developer has a proposed cost estimate of $3,000M with an 80% learning rate
- This can be shown to be an optimistic estimate by the developer
  – *An 80% learning rate implies a cost of about $5,600, while a $3,000M cost estimate implies a learning rate of about 70%*
- The decision maker should come away from this thinking that the developer will…
  – *Need a much more aggressive learning rate in order to deliver at $3,000M*

    or

  – *Need to start with a very low, optimistic first unit cost to deliver at $3,000M with an 80% learning rate*

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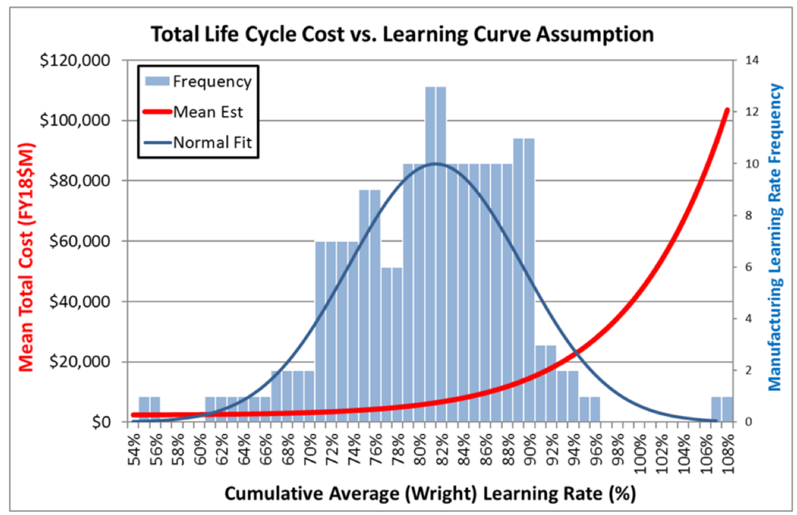

Conclusion

- The Learning Rate Sensitivity Model is one of the tools used by The Aerospace Corporation to assess reasonableness of proposed cost estimates

- Useful in evaluating credibility of one or more cost estimates which might have substantially different learning rate assumptions
  - *Allows one to estimate the learning rate that would be necessary to deliver a high rate production program given a developer's proposed cost*
  - *Provides a basis for assessing reasonableness of learning assumptions*

- Can also be used to estimate sensitivity of cost estimates to learning assumptions, especially in high rate production acquisitions

- Further research:
  - *Historical data from Argote and Epple are predominantly large hardware and labor intensive systems which may be comparable to traditional spacecraft manufacturing methods*
  - *But, as spacecraft designs trend toward microsats and cubesats, the traditional learning curve theories described herein may not adequately apply*

Tool to assess reasonableness of cost estimates versus learning rate assumptions