Estimating Life Cycle Costs at the Skunk Works®

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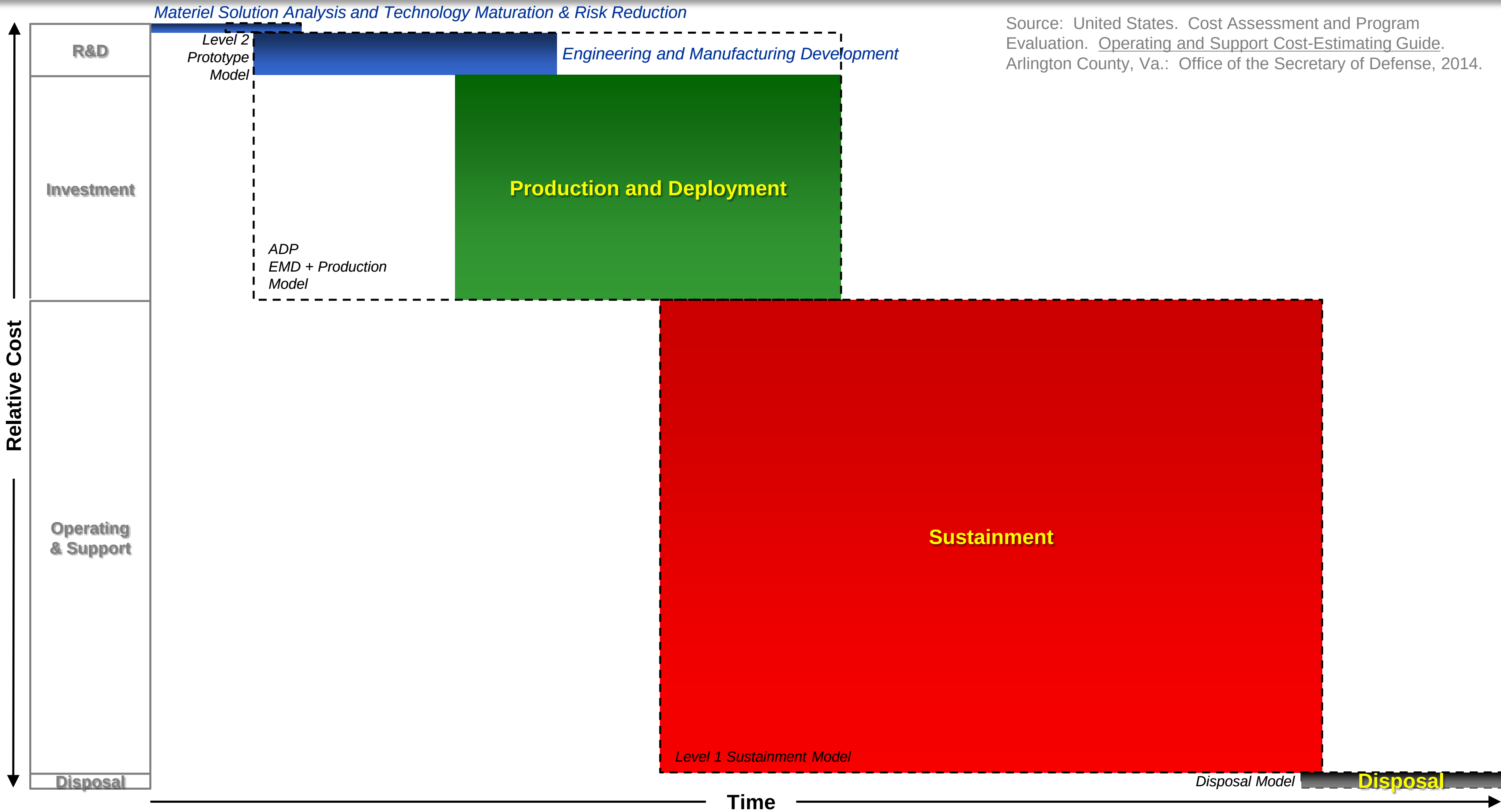
LOCKHEED MARTIN

Summary

We have established a Life Cycle Cost estimating suite of models that parametrically predicts Prototype, Engineering & Manufacturing Development, Production, Sustainment, and Disposal costs. The establishment of Sustainment cost estimating relationship equations, the adoption of a Government-funded Disposal white paper results, and standardizing model design enables our internal customers to better understand our estimating philosophy and significantly improve the turnaround time of our estimates.

ADP Life Cycle Cost Models



Source: United States. Cost Assessment and Program Evaluation. Operating and Support Cost-Estimating Guide. Arlington County, Va.: Office of the Secretary of Defense, 2014.

We have models that cover CAPE LCC from Prototype to Disposal

Aircraft Programs Used in the Prototype Model


XP-80 Lulu Belle
(1944)

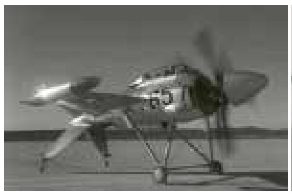

XP2V-1 Neptune
(1945)


XR6O-1 Constitution
(1946)


Model 75 Saturn
(1947)


XF-90
(1949)


XF-104n Starfighter
(1954)


XFV-1 Pogo
(1954)


YC-130 Hercules
(1954)


U-2
(1955)

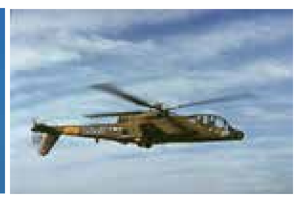

JetStar
(1957)


LASA-60 Santa Maria
(1959)


XH-51A
(1962)

XV-4A Hummingbird
(1962)


L-286
(1965)

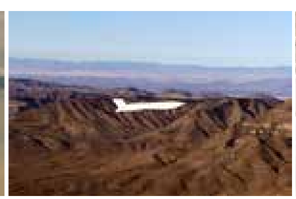

AH-56A Cheyenne
(1967)

XV-4B Hummingbird
(1968)


YF-16
(1973)

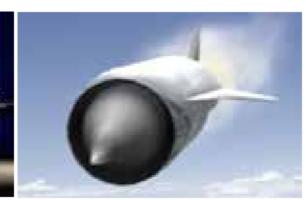
Have Blue
(1977)


YF-22A ATF
(1990)


AGM-158 JASSM
(1999)


X-35
(2000)


P-175 Polecat
(2005)


RATTLRS
(no flight test)


X-55
(2009)

24 programs since Skunk Works® inception

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Aircraft Programs Used in the EMD Model

C-130A Hercules
1955

F-104A Starfighter
1956

F-104B Starfighter
1957

P-3A Orion
1961

P-3C Orion
1963

C-141 Starlifter
1963

C-5A Galaxy
1969

L-1011 TriStar
1970

S-3A Viking
1972

F-22 Raptor
1997

F-117 Nighthawk
1981

F-16E/F Blk 60
Fighting Falcon
2003

F-35 Lightning II
2006

The inclusions of subsequent versions of the same aircraft enabled us to determine the statistical significance of the equivalent new air vehicle design independent variable

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Aircraft Programs Used in the Sustainment Model

- Beechcraft C-12 Huron
- Beechcraft T-6A Texan II
- Bell TH-1H Iroquois
- Bell UH-1N Twin Huey
- Bell Boeing CV-22B Osprey
- Boeing B-52H Stratofortress
- Boeing C-17A Globemaster III
- Boeing C-40 Clipper
- Boeing E-3 Sentry
- Boeing KC-135 Stratotanker
- Boeing RC-135
- Cirrus T-53A
- Fairchild Republic A-10C Thunderbolt II
- General Atomics MQ-1B Predator
- General Atomics MQ-9 Reaper
- General Dynamics F-16 Fighting Falcon
- Learjet C-21A
- Lockheed AC-130
- Lockheed C-5 Galaxy
- Lockheed C-130H Hercules
- Lockheed EC-130H Compass Call
- Lockheed LC-130H
- Lockheed MC-130
- Lockheed U-2
- Lockheed WC-130J
- Lockheed Martin C-130J Super Hercules
- Lockheed Martin F-22 Raptor
- Lockheed Martin F-35A Lightning II
- McDonnell Douglas F-15A-D Eagle
- McDonnell Douglas F-15E Strike Eagle
- McDonnell Douglas KC-10A Extender
- Northrop T-38 Talon
- Northrop Grumman B-2A Spirit
- Northrop Grumman E-8 Joint STARS
- Northrop Grumman RQ-4 Global Hawk
- Raytheon T-1A Jayhawk
- Rockwell B-1 Lancer
- Sikorsky HH-60 Pave Hawk

38 air vehicles – all in current USAF inventory. Data retrieved from Government sources

Disposal Model

Disposal model CER equations are retrieved from the following Air Force Cost Analysis Agency-directed document:

Kaye, Mark F., Bruce R. Harmon, Alexander O. Gallo, and John E. MacCarthy. Predicting Disposal Costs for United States Air Force Aircraft (Presentation). Alexandria, Va.: Institute for Defense Analyses, 2015

Presentation may be downloaded from the following Defense Technical Information Center URL:

http://www.dtic.mil/dtic/tr/fulltext/u2/a617955.pdf

Independent Variables

Independent Variable (P = Primary, I = Secondary)	Prototype	EMD	Manufacturing T1	Sustainment	Disposal
Weight (pounds)	P	I	P		P
Schedule (months)	P	P			
% New Design		P			
Vehicle Complexity	I				
State of the Art	I				
Speed	I				
Technical Readiness Level		I			
Wing Loading (pounds per square foot)		I			
Government Personnel				P	
Annual Fuel Consumption (gallons)				I	
Annual Flying Time (hours)				I	
System Improvement				I	
Footprint (square feet)					I
Time in Storage (years)					I
Storage Maintenance (per year)					I
Re-Preservation (per storage)					I

Apart from Weight, little commonality between models

Independent Dummy Variables

Independent Dummy Variable	Prototype	EMD	Manufacturing T1	Sustainment	Disposal
Requirements (Minimum/Normal)	I				
Programmatic (Experimental/Pre-Production)	I				
Advanced Manufacturing Processes	I		I		
Propulsion (Jet/Propeller)				I	
Stealth	I	I			
Bomber		I			I
Fighter/Attack	I			I	I
Transport		I			
Trainer				I	
Operational					I
Reclamation					I

Aircraft type (blue) has notable impact in determining costs across all LCC phases

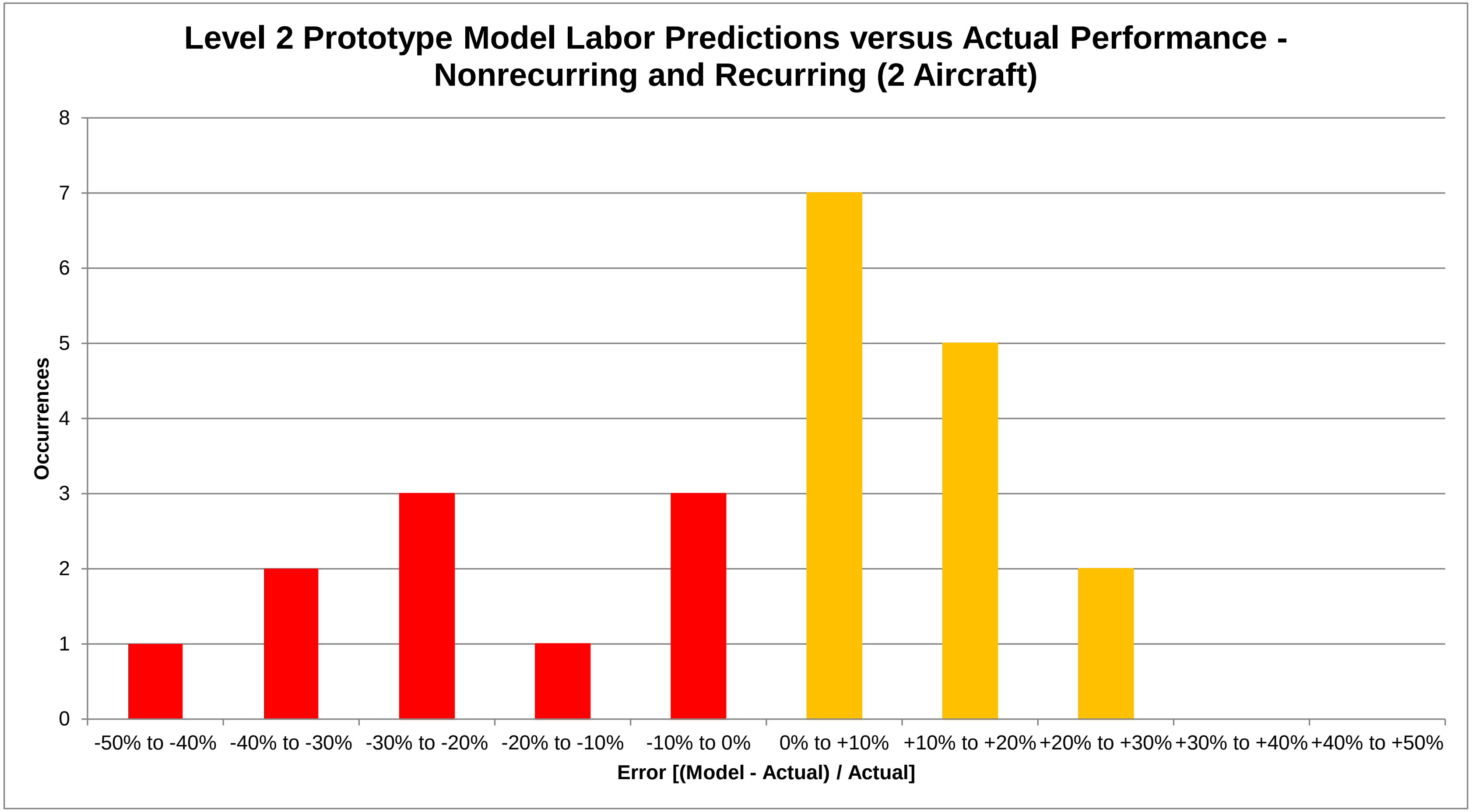
Models Statistics

Item	Prototype	EMD	Manufacturing T1	Sustainment	Disposal
Number of Observations	24	13	54	38	14
Years of First Flight Range	1944 – 2009	1955 – 2006	1939 – 2009	1952 – 2011	
Aircraft Types	5	3	5	8	4
Empty Weight Range (pounds)	880 – 124,306	12,139 – 316,149	4,360 – 380,000	1,130 – 380,000	4k – 325k
Schedule Length (months)	14 – 60	51 – 173			
Goodness of Fit Range (r^2)	0.62 – 0.96	0.80 – 0.97		0.82 – 0.98 *	0.68 – 0.89
Goodness of Fit (median CER equation r^2)	0.84	0.90	0.97	0.94	0.87
Accuracy-Bias (prediction under/over actual)	10 under / 14 over	6 under / 7 over	30 under / 24 over	21 under / 17 over	
Accuracy-Error (median observation error from 0)	+1.4%	+0.4%	-2.7%	-3.5%	
Precision (1/2 of predictions are within…of actual)	16.7%	8.5%	13.2%	18.3%	
Precision (3/4 of predictions are within…of actual)	20.3%	25.2%	21.7%	29.7%	

*applies to 4 of 6 cost element structure items (90% of total sustainment cost); non-statistically-derived equations are used for the remaining two elements

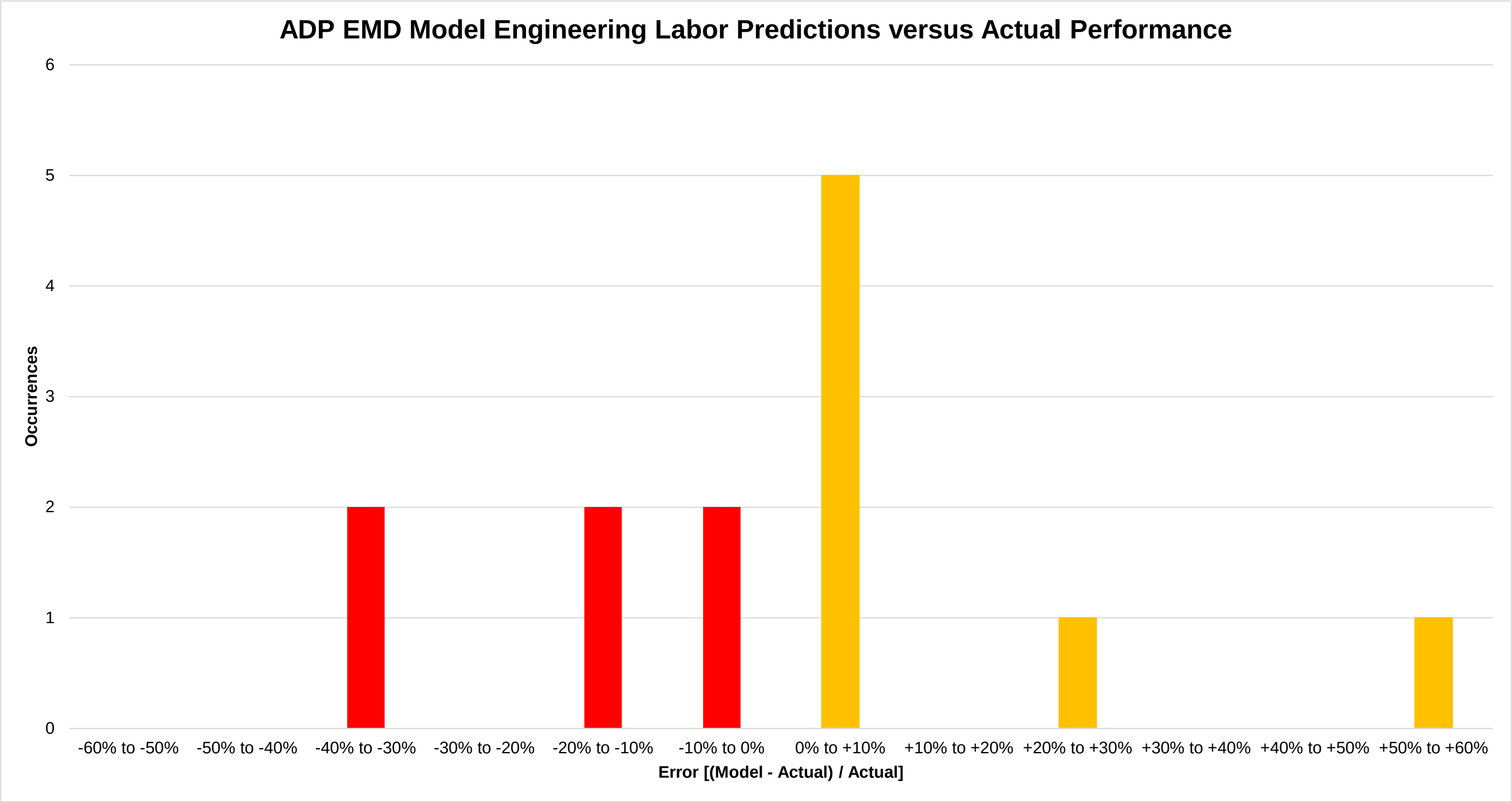
Good fit, accurate, usually rough order-of-magnitude precise

Prototype Model Validation



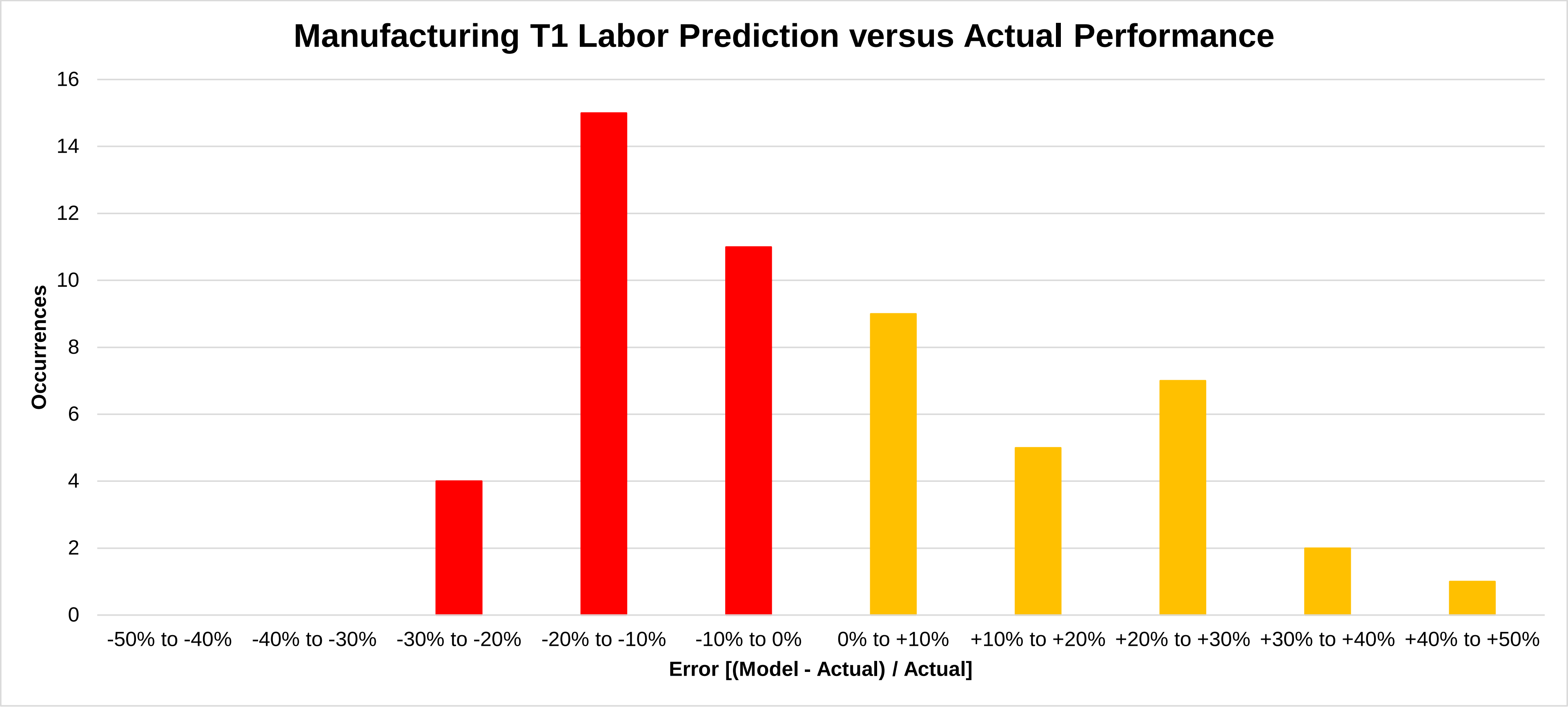
10 of 24 (42%) observations fall within 10%, 16 of 24 (67%) observations fall within 20%

EMD Model Validation



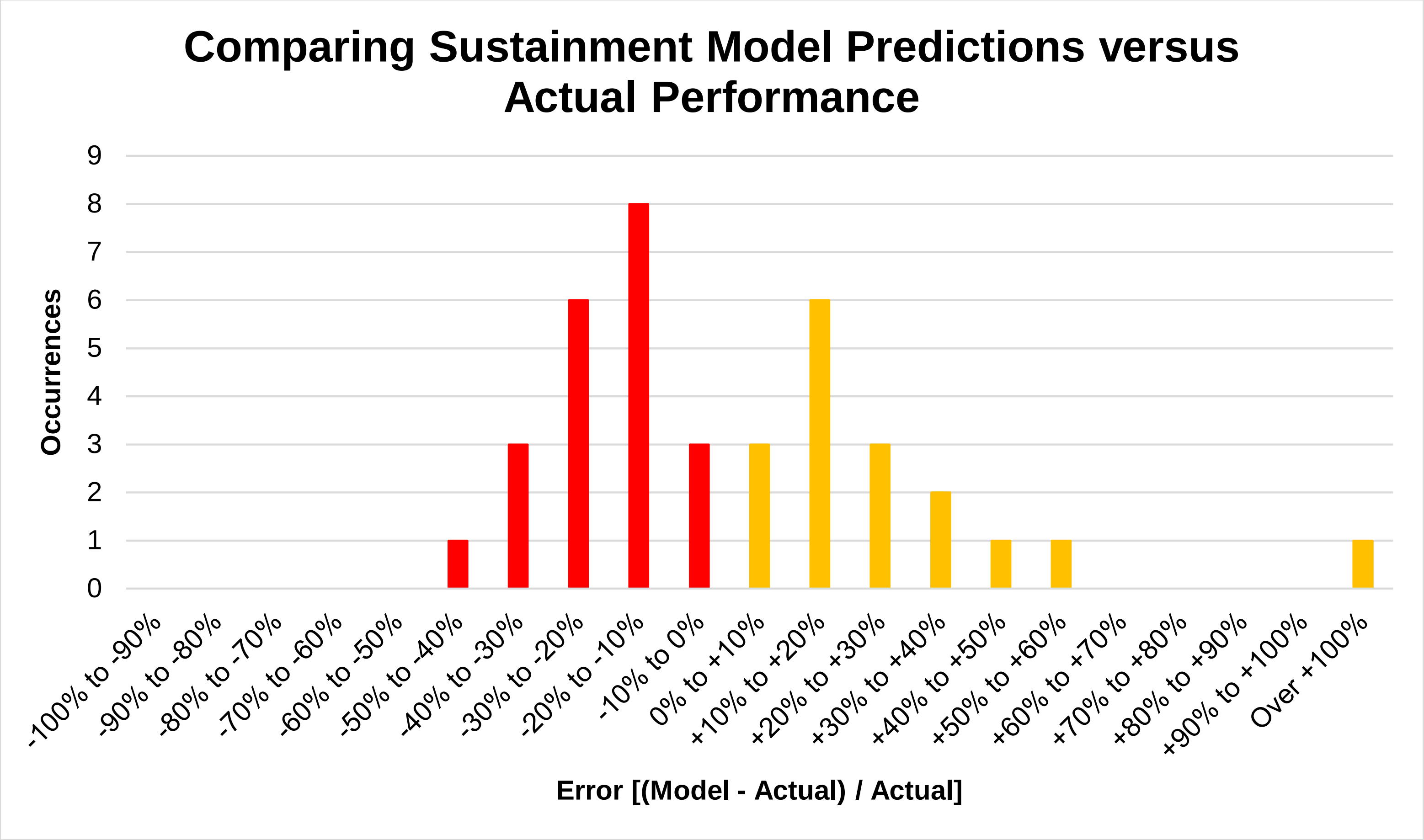
7 of 13 (54%) observations fall within 10%, 9 of 13 (69%) observations fall within 20%

Manufacturing T1 Equation Validation



20 of 54 (37%) observations fall within 10%, 40 of 54 (74%) observations fall within 20%

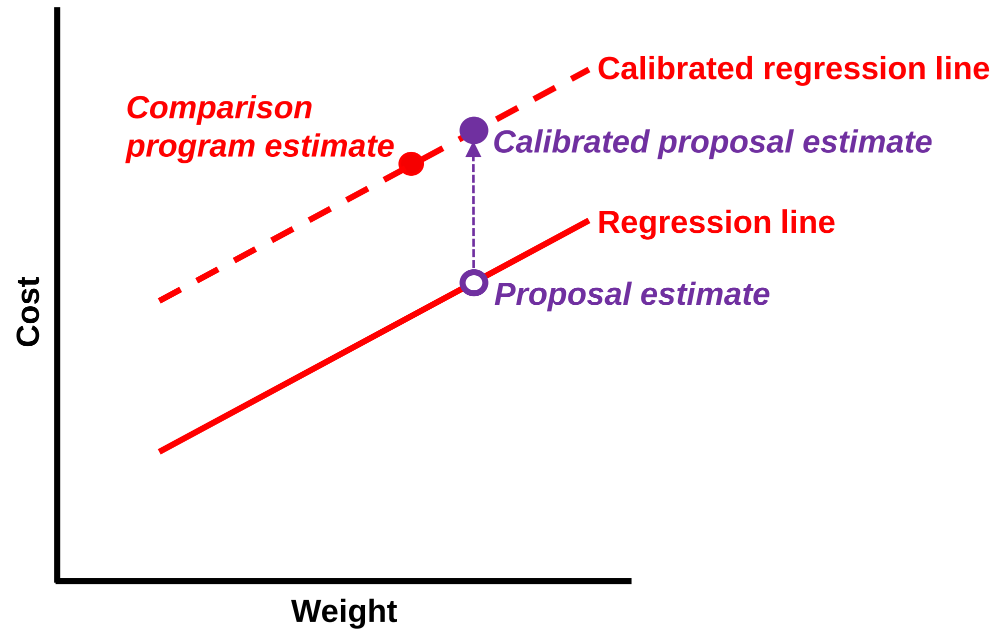
Sustainment Model Validation



6 of 38 (16%) observations fall within 10%, 20 of 38 (53%) observations fall within 20%

Calibration

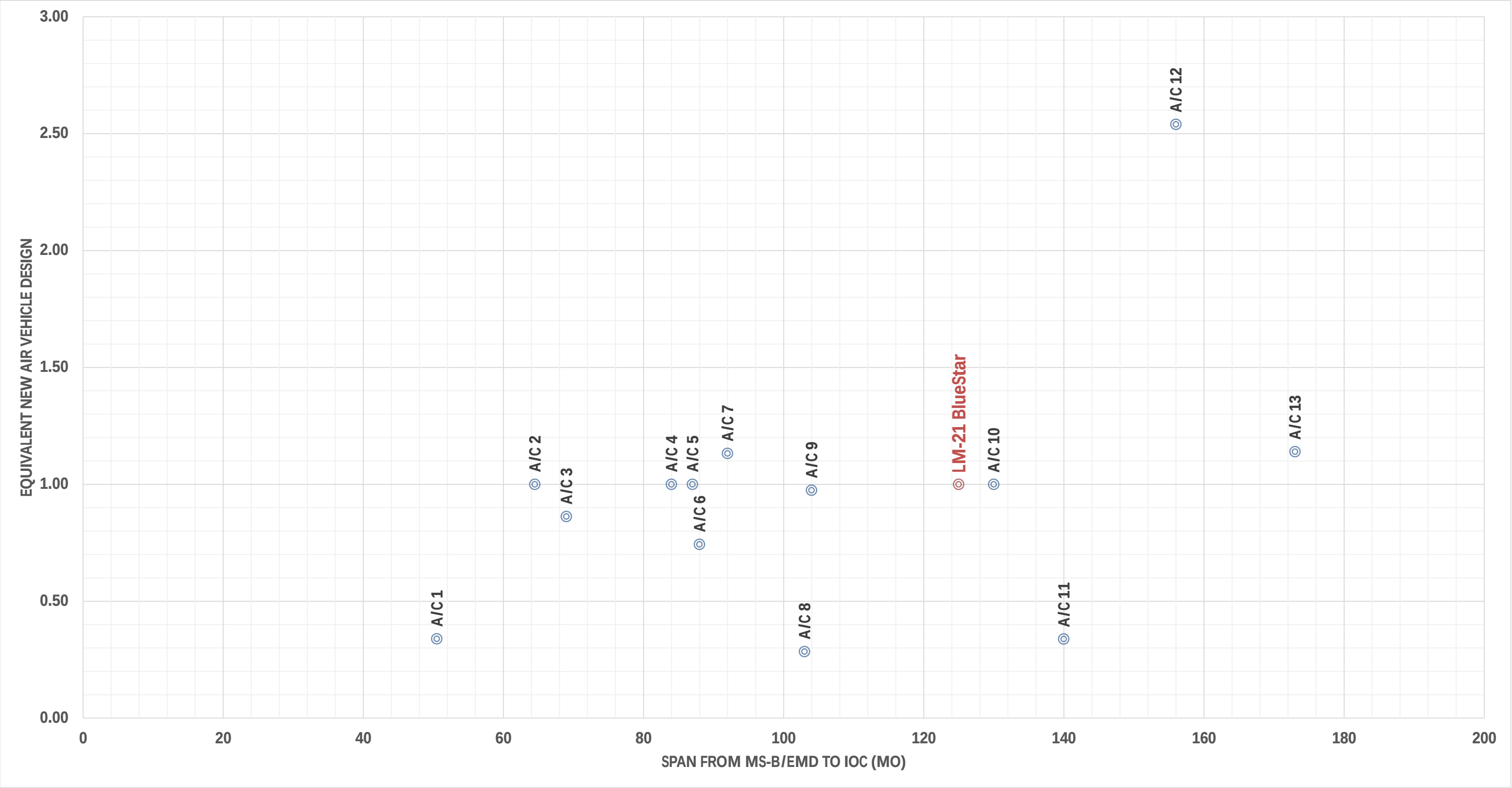
There are instances where the model significantly under/over-predicts actual performance of an air vehicle program. This becomes critical when we want to predict the cost of a program that is similar to the under/over-predicted program. To alleviate this problem, we introduce the concept of calibration into our prototype, EMD, and sustainment models



The scale of the analogous relationship is defined by the CER equation

Sample Position Map: "LM-21 BlueStar*"

**…a fictionalized, 21st century, unitized composite fuselage version of the L-1011 TriStar*



The position map helps identify which, if any, of the programs the proposed item could be calibrated off of

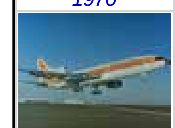
Calibration Factors: "LM-21 BlueStar"

Program Designation	Composite Factor	No Calibration Factor	C-130A	F-104A	F-104B	P-3A	P-3C	C-141	C-5A	L-1011	S-3A	F-22	F-117	F-16E/F Blk60	F-35
Name of Aircraft			Hercules	Starfighter	Starfighter	Orion	Orion	Starlifter	Galaxy	TriStar	Viking	Raptor	Nighthawk	Fighting Falcon	Lightning II
Type of Aircraft			Transport	Fighter	Fighter	Patrol	Patrol	Transport	Transport	Transport	Anti-Sub	Fighter	Fighter	Fighter	Fighter
Year Of First Flight			1955	1956	1957	1961	1963	1963	1969	1970	1972	1997	1981	2003	2006
															
Airframe Structure + Airframe IAT&CO + Air Vehicle IAT&CO	100%	0%	0%	0%	0%	0%	0%	0%	0%	100%	0%	0%	0%	0%	0%
Propulsion	100%	0%	0%	0%	0%	0%	0%	0%	0%	100%	0%	0%	0%	0%	0%
Vehicle Systems	100%	0%	0%	0%	0%	0%	0%	0%	0%	100%	0%	0%	0%	0%	0%
Mission Systems	100%	0%	0%	0%	0%	0%	0%	0%	0%	100%	0%	0%	0%	0%	0%
Armament	100%	0%	0%	0%	0%	0%	0%	0%	0%	100%	0%	0%	0%	0%	0%
Systems Engineering	100%	0%	0%	0%	0%	0%	0%	0%	0%	100%	0%	0%	0%	0%	0%
System Test and Evaluation	100%	0%	0%	0%	0%	0%	0%	0%	0%	100%	0%	0%	0%	0%	0%
Airframe Structure + Airframe IAT&CO + Air Vehicle IAT&CO	0.8923	1.0000	0.7494	0.9515	3.1158	0.5711	1.3226	0.8617	1.5926	0.8923	0.6835	1.1000	0.3766	0.7119	2.4142
Propulsion	2.1026	1.0000	2.0149	0.6838	1.0000	1.5075	1.0000	1.6978	1.8840	2.1026	0.1022	0.2647	0.6228	1.8682	2.2749
Vehicle Systems	1.6768	1.0000	0.3758	0.2063	5.8271	0.7664	0.4680	1.5883	2.2318	1.6768	0.3435	1.2620	1.1303	0.9837	2.1548
Mission Systems	0.2780	1.0000	0.0477	0.3432	0.5270	1.0561	1.6182	2.2636	6.1351	0.2780	1.1787	0.6046	8.9895	1.9587	1.4008
Armament	0.0000	1.0000	0.0000	1.2474	1.0846	1.2872	0.7523	0.0000	0.0000	0.0000	0.5116	1.4921	1.0000	1.0000	1.0000
Systems Engineering	0.7255	1.0000	1.2081	1.3043	1.0000	0.2177	1.0000	0.7710	2.2326	0.7255	3.1052	0.7048	1.0000	1.0000	1.0666
System Test and Evaluation	1.5786	1.0000	0.7456	1.1436	0.8050	0.2583	0.5051	1.1159	2.3842	1.5786	1.5066	0.8393	1.7886	2.2492	0.5228

Factor = actual performance / model prediction

Inputting L-1011 characteristics and setting L-1011 calibration factor allocation to 100% would yield L-1011 actual performance results

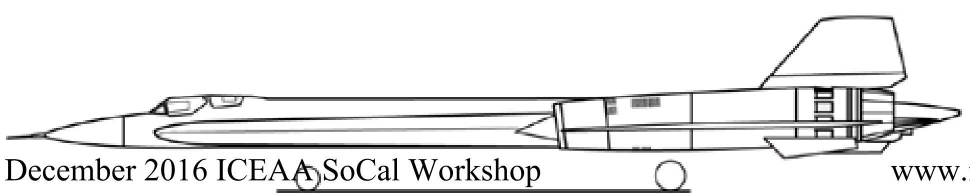
- ***The application of a calibration factor will scale the proposed air vehicle off of similar air vehicle actual performance. This should increase the accuracy of our estimate***
- ***More than one air vehicle can be used to create a composite series of factors***

Program Designation	Composite Factor	L-1011
Name of Aircraft		TriStar
Type of Aircraft		Transport
Year Of First Flight		1970
		
Airframe Structure + Airframe IAT&CO + Air Vehicle IAT&CO	100%	100%
Propulsion	100%	100%
Vehicle Systems	100%	100%
Mission Systems	100%	100%
Armament	100%	100%
Systems Engineering	100%	100%
System Test and Evaluation	100%	100%
Airframe Structure + Airframe IAT&CO + Air Vehicle IAT&CO	0.8923	0.8923
Propulsion	2.1026	2.1026
Vehicle Systems	1.6768	1.6768
Mission Systems	0.2780	0.2780
Armament	0.0000	0.0000
Systems Engineering	0.7255	0.7255
System Test and Evaluation	1.5786	1.5786

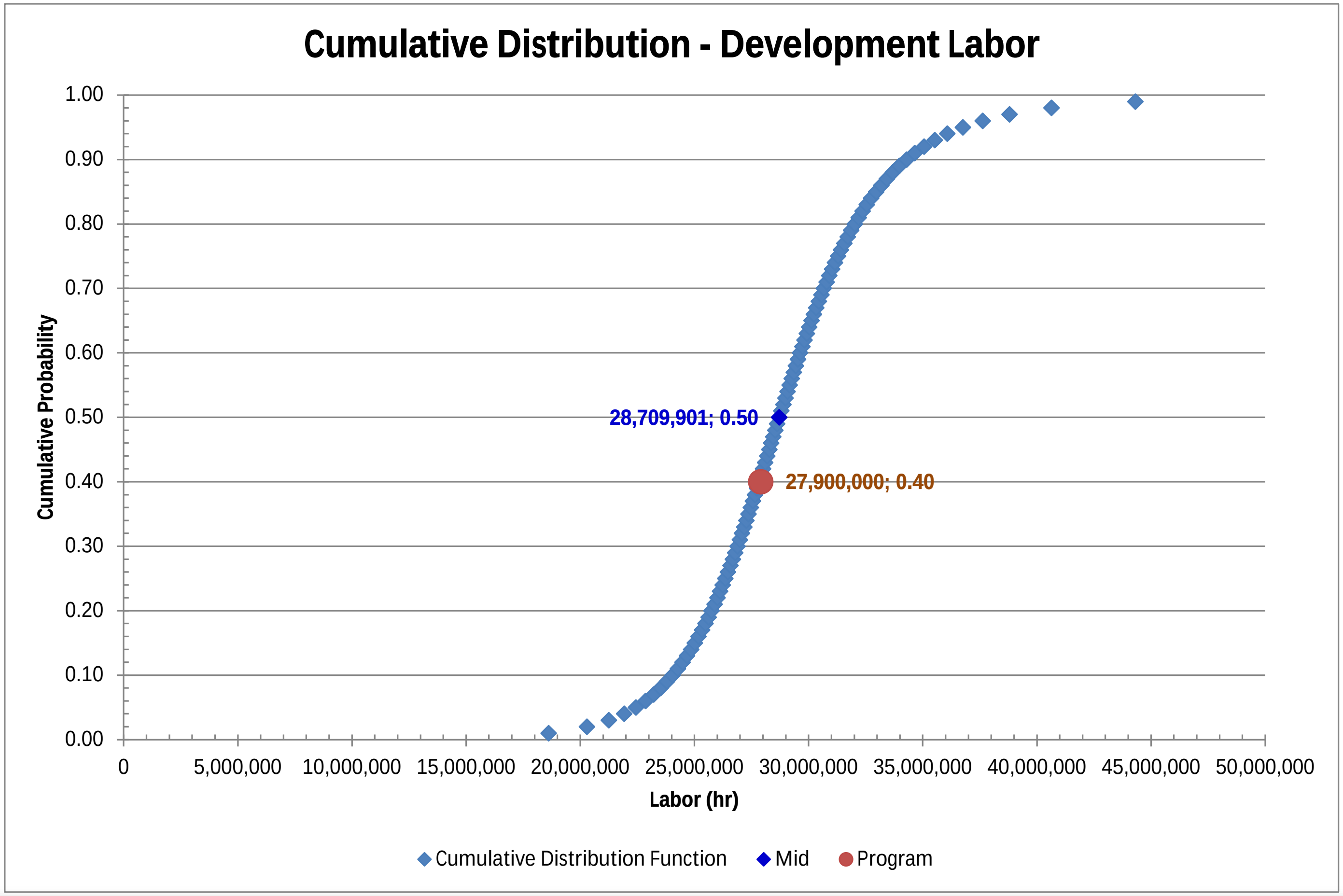
Model Features

Item	Prototype	EMD	Production	Sustainment	Disposal
MIL-STD-881C WBS	Supplier Items	P	P	*	
CER Equation Coefficient as Model Input	P	P	P	P	P
Parametrically Determined Schedule		P			
Calibration	P	P		P	
Schedule	2016 - 2025	2016 - 2024	2016 – 2044	50 years	None
Total Cost Output (BY$)	P	P	P	P	P
Cost Output by WBS Element	Supplier Items	P	P	P	
Cost Output by Year (BY$)		P	P	P	
Cost Output by Year (TY$)		P			
Risk	P	P	P	P	
Comparison Against Actual Performance	P	P		P	

*uses OSD cost element structure

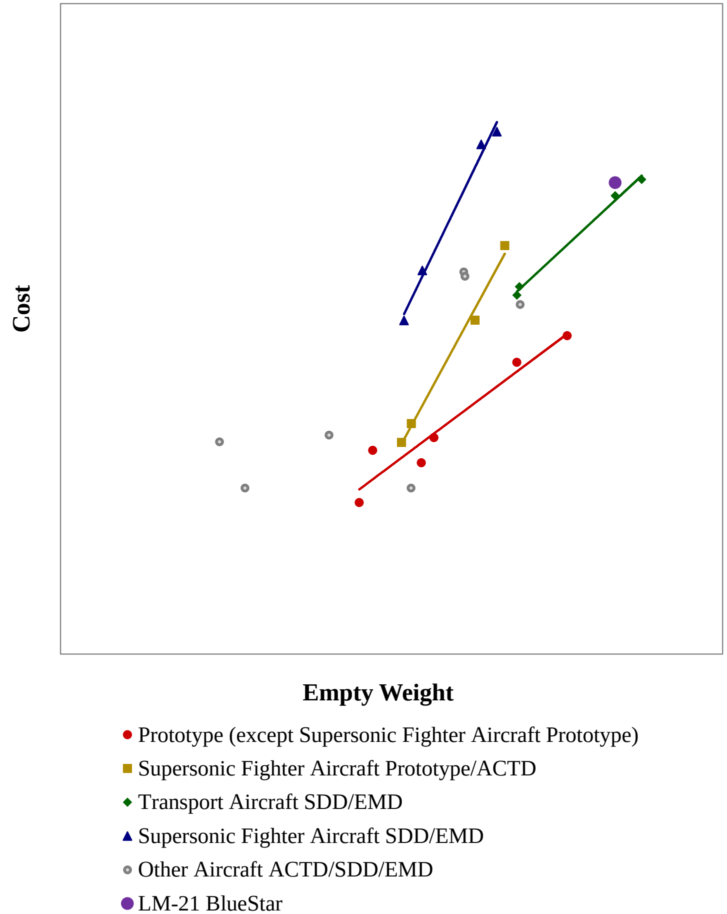


Sample Risk Output: "LM-21 BlueStar"



Program position is a discrete input that is used to determine risk position against parametric estimate

Comparing "LM-21 BlueStar" Result Against Other Program Actual Performance



Separating Aircraft by Type and Program Phase Dramatically Improves Goodness of Fit Results ($0.93 < r^2 < 0.99$)